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FREE FALL AND EVAPORATION OF JP-1 JET FUEL

DROPLETS IN A QUIET ATMOSPHERE

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SUMMARY

In connection with the problem of the dispersion of jet fuel jetti-
soned at altitude, an analytical investigation was made of the free fall
with and without evaporation in a quiet atmosphere of JP-1 jet fuel drop-
lets of average composition. (Evaporation rates of commercial kerosene
fuels are comparable with that of JP-1.) As in a similar previous study
of JP-4 fuel (NASA TN D-33), the significant physical characteristics of
JP-1 were approximated by replacing the chemically complex fuel by a
mixture of ten petroleum "fractions" having predictable evaporation rates.

Altitudes reached after given times of fall from a jettisoning alti-
tude and ratio of residual mass of a droplet (at a given altitude) to
original mass are given for a number of combinations of the following:
initial droplet diameter, 250, 500, 750, 1000, 1500, and 2000 microns;
jettisoning altitude, 13,000, 11,000, 9000, 7000, 5000, and 3000 feet;
and sea-level air temperatures, -30°, -15°, 0°, 15°, 30°, and 45° C.

As in the study of JP-4, it was found that temperature was the prin-
cipal controlling variable. Evaporation rates of JP-1 droplets are very
low below 0° C; even at temperatures between 10° and 20° C they remain
moderate. At temperatures above 20° C, JP-1 droplet average evaporation
rates gradually approach average rates of JP-4 droplets.

Accordingly, JP-1 droplet evaporation may be ignored for many engi-
neering purposes when sea-level temperatures are 0° C or lower. Evapora-
tion rates between 0° and 10° C are not sufficiently large to affect
materially the liquid concentrations present after moderate distances of
fall. Ground contaminations will be significantly greater in the case
of JP-1 than for JP-4 except at the very low temperatures at which neither
fuel evaporates at a significant rate (below -15° C). In general, evapora-
tion rates of JP-1 are comparable with those of JP-4 at temperatures 20° C
higher. It follows that dispersal and ground contamination estimates can
be made for either fuel by using appropriate results for the other fuel,
due allowance being made for this 20° C differential.

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INTRODUCTION

As was remarked in previous reports (refs. 1 and 2), it occasionally becomes necessary to jettison at altitude all or a major fraction of the fuel load of an aircraft. Calculations of concentration of liquid fuel at given altitudes and times after release (ref. 2) require knowledge of both the spatial distribution of droplets and of the rates of decrease of droplet mass as the result of evaporation. Extensive results were given in reference 1 concerning fall in a quiet atmosphere both with and without evaporation of the jet fuel JP-4.

Since it was known that JP-1 is not as volatile as JP-4, similar calculations were desirable for JP-1. Accordingly, a digital computer program was prepared which was, in many respects, equivalent to the original program (ref. 1) but which incorporated a number of improvements. In the original program, the rate of evaporation of each of ten hypothetical hydrocarbon fractions collectively simulating the real mixture was calculated for a droplet of a particular size and composition subjected to appropriate atmospheric conditions. The total rate of evaporation was then obtained as the simple sum of the separate rates (due regard having been taken of Raoult's Law), and the droplet was permitted to fall while evaporating at that rate for a small increment of time. At the end of such a time step, all relevant calculations were repeated, and this procedure was continued until either the droplet disappeared or reached ground level. As an approximation, the droplet temperature was taken to be the air temperature. In the present program, the principal change was the removal of the latter approximation; decrease of droplet temperature as the result of evaporative cooling is now taken into account. The revised program is discussed in further detail in appendix A.

Extensive calculations concerning free fall with and without evaporation of JP-1 were made with the revised program; a few additional calculations were made concerning JP-4.

The results of these calculations are presented and discussed in the principal section of this report. Remarks are then made concerning the possible application of the new results to the problem of the dispersal of jettisoned jet fuel and the unresolved problem of ground contamination.

In general, the term "air temperature" is used throughout to denote "sea-level air temperature" and should be so understood except where air temperature at altitude is explicitly mentioned or clearly implied. The terms "jettisoning altitude," "starting altitude," and "initial altitude" are used synonymously.

Appreciation is expressed of the work of Miss Frances J. Schubert of Lewis in connection with this investigation. Miss Schubert developed the block diagram of the revised program in collaboration with the author and coded the program in detail for the ERA 1103 computer.

RESULTS AND DISCUSSION

The results of the JP-1 calculations and of a few comparison JP-4 calculations are exhibited in figures 1 to 6.

Four kinds of presentation are made in these figures. In figures 1 and 2, droplet altitude is plotted as a function of time. In figures 3 and 4, the ratio of droplet residual mass to original mass is indicated as a function of droplet altitude. In figure 5, the effect of starting altitude on distance of fall for a given fractional mass loss is given more directly. Finally, mass loss rate is presented as a function of air temperature in figure 6. These results are considered below in greater detail.

The combinations of droplet diameter, jettisoning altitude, and sea-level temperature for which results are given in figures 1 to 4 are indicated in table I. It should be noted that extensive results are given for the jettisoning altitude 3000 feet and that fewer results, principally of use in the making of comparisons or in the estimation of trends, are given at the higher altitudes. Further, results of fall-with-evaporation calculations for 250-micron droplets alone are given for the -30° C temperature because total mass losses of larger droplets are in general ignorable at such temperatures.

In figure 1, droplet altitude is given as a function of time for several starting altitudes; the parameter combinations are as indicated in table I. In particular, fall histories are presented for situations in which, in general, significant droplet evaporation is occurring. However, a number of histories are given of nonevaporating droplets for starting altitudes ranging from 3000 to 9000 feet; these histories represent limiting ones in the obvious sense that distances of fall are greatest for nonevaporating droplets.

Distance of fall varies linearly with time in the case of many of these results, particularly at the large-diameter low-temperature combinations. However, marked deviations occur (particularly for falls beginning at the lower altitudes) at as low a temperature as -15° C in the case of the 250-micron results, and at temperatures between 0° and 15° C in the case of the 500-micron results. Such deviations are clearly associated with the significant evaporation occurring at such diameters at the temperatures in question (and exhibited directly in figs. 3 and 4).

At higher temperatures, deviations from linearity of the calculated relation between droplet altitude and time become very great; droplets having diameters of less than about 750 microns come virtually to rest after periods of fall varying, for example, at 30° C from 2 to 5 minutes at 250 microns to 5 to 10 minutes at 500 microns, the period increasing

with increasing jettisoning altitude. The substantial increases with altitude of period of significant fall are caused principally by the decrease of evaporation rate associated with the lower temperatures existing at the higher altitudes. (This effect is discussed below in greater detail.) However, secondary effects of changes of air density and viscosity are also present, particularly at altitudes above 7000 feet.

Detailed discussion of figure 2, a comparison of fall histories of JP-1 and JP-4 droplets, is deferred.

In figure 3, the ratio of the residual mass (of a JP-1 droplet) to original mass is given for the parameter combinations indicated in table I. The 3000-foot results, as in the case of figure 1, are the most complete.

The omission of evaporation results for droplets larger than 250 microns at a temperature of -30° C can be understood when the 250- and 500-micron results for a starting altitude of 3000 feet are considered (fig. 3(c)). At ground level (after a fall of 3000 ft), 0.87 of the original mass of a 250-micron droplet is still present; the droplet diameter is then 238 microns. On the other hand, at -15° C, 0.43 of the original mass is still present at ground level, and the droplet diameter has decreased to 188 microns. Finally, at 0° C, less than 0.04 of the original (250-micron) droplet is left after a fall of only 1800 feet; at the altitude of 1200 feet the diameter is 82 microns and the falling speed only 0.57 foot per second. In comparison, 0.87 of the original mass of a droplet that had an original diameter of 500 microns is still present at ground level at a temperature of -15° C, while 0.54 of the original mass is present at 0° C.

On the whole, the major fact established by these results is that, despite the low evaporation rate of JP-1, significant fractions of smaller JP-1 droplets are lost during falls of less than 2000 feet at air temperatures greater than -15° C. As additional examples, the following are the losses in the case of a 500-micron droplet falling 1000 feet from an initial altitude of 3000 feet: 15 percent at 0° C, 47 percent at 15° C, and 96 percent at 30° C. No portion of a 500-micron droplet would be present after a fall of more than about 500 feet at 45° C from an altitude of 3000 feet. Losses in the case of a 1000-micron droplet are less severe but are nevertheless significant at temperatures above 0° C. From the same altitude (3000 ft), such a droplet would lose 12 percent of its original mass during a 1000-foot fall at 15° C, and would lose 33 and 70 percent during such a fall at 30° and 45° C, respectively. Fractional loss rates for a 2000-micron JP-1 droplet at a given air temperature are comparable with, though somewhat less than, those for a 1000-micron droplet at a temperature 15° C lower, and the same relation holds between loss rates for 1000- and 500-micron droplets (as the preceding numerical examples indicate).

Loss rates of droplets at given sea-level air temperatures, but for starting altitudes other than 3000 feet, are affected principally by the decrease of temperature with altitude and secondarily by changes in other air properties. The temperature effects are of such high relative importance as to warrant neglect of others when estimating the probable influence of altitude. For example, a 500-micron droplet falling from 11,000 feet will lose about 50 percent of its mass during the first 1000 feet of fall when the (sea-level) air temperature is 30° C (the evaporation history has not been plotted in this instance). The air temperature at 11,000 feet is about 8° C under these circumstances. It happens that at a sea-level temperature of 15° C the air temperature at 3000 feet will be about 9° C, and it is therefore interesting in this connection to recall the 47-percent loss (previously cited) of a 500-micron droplet during a fall of 1000 feet from a jettisoning altitude of 3000 feet at 15° C. The air temperature at altitude in the latter case, it will be noted, is about 1° C higher than in the case of the fall from 11,000 feet (sea-level temperature of 30° C), but the loss rate in the latter situation is nevertheless slightly higher. The difference, clearly small and of little practical significance, is ascribable principally to the increasing mass-transfer rates associated with the increase of diffusion coefficients stemming, in turn, from the decrease of pressure with altitude. Falling speeds are slightly higher at the higher altitudes, but Reynolds numbers are slightly lower (tending to decrease, but not significantly, the mass-transfer rates).

Fall histories of JP-1 and JP-4 droplets are compared in figures 2 and 4. Comparisons are also provided of JP-4 results as obtained with the original program (IBM 650 computer) and the present one (ERA 1103).

In figure 2, droplet altitude is plotted as a function of time for the two fuels. Results are given for 750- and 2000-micron droplets falling from 5000 feet at air temperatures of 0° and 30° C. In the case of JP-4, these results are given as calculated with both the original and the present programs.

Marked differences between fall histories of JP-1 and JP-4 droplets become evident within minutes at droplet diameters of less than 1000 microns. This is clearly shown even in the 0° C results. JP-1 droplets of 750-micron diameter, for example, fall about 15 percent faster (on the average) during the first 240 seconds of fall from a 5000-foot altitude than 750-micron JP-4 droplets. For 2000-micron droplets, the difference decreases to about 7 percent; for droplets of both sizes the differences in distances of fall between the two fuels is about 300 feet. The differences between the fuels are greater at the 30° C temperature.

These differences are ascribable almost entirely to the different mean rates of evaporation of JP-1 and JP-4. JP-1 is about 2 percent heavier, but such a difference will affect falling speeds only trivially.

(The two sets of JP-4 results exhibited in fig. 2 are in excellent agreement. As indicated in the INTRODUCTION, cooling of a droplet through evaporation, which was not considered in the original 650 program, is now taken into account. The effect of such cooling on evaporation rates is reflected in the 1103 results.)

The differences in evaporation rate between JP-1 and JP-4 are well illustrated in figure 4, in which the residual mass is plotted as a function of altitude for 750- and 2000-micron droplets of both JP-1 and JP-4 falling from an altitude of 5000 feet at air temperatures of 0° and 30° C. The much lower mean rate of evaporation of JP-1 is evident, but, in addition, the much greater variations in evaporation rate of a single JP-4 droplet during a free fall are clearly indicated. At 0° C, little loss of a 2000-micron JP-1 droplet occurs, but a JP-4 2000-micron droplet will lose one-third of its mass before striking the ground. At the same temperature, the loss rate of a 750-micron JP-4 droplet is, on the average, over twice as great as that of a JP-1 droplet during such a 5000-foot fall. Incomplete results are available for JP-4 at 30° C, but the differences are, of course, greater at that temperature.

Inspection of a greater number of mass loss results for the two fuels reveals that at temperatures between -15° and 25° C mean loss rates of JP-1 at given temperatures are roughly equal to those of JP-4 at temperatures lower by about 20° C. At the lowest temperatures, as has been mentioned, little evaporation of either fuel occurs, whereas JP-1 mean evaporation rates increase rapidly beyond about 25° C and tend to become equal to those of JP-4. The temperature at which this tends to occur varies somewhat with droplet size; this point is discussed again in connection with the subsequent discussion of figure 6.

In figure 5, distances of fall of 500- and 2000-micron droplets are plotted as functions of starting altitude for the fixed total mass losses of 25, 50, and 75 percent for the temperatures 0° and 30° C, where the results can be plotted; at 0° C, 2000-micron droplets will have lost only 6.5 percent of the original mass during a fall to the ground from an altitude of 13,000 feet, whereas the loss has decreased only trivially - to about 6 percent - for a fall to the ground from an altitude of 7000 feet. Accordingly, even a 25-percent loss is never approached in the case of a 2000-micron JP-1 droplet falling from any altitude of present interest when the ground temperature is 0° C. In addition, it is of interest that the (assumed) 12° C decrease of temperature between 7000 and 13,000 feet is nearly sufficient to offset completely the increased period of evaporation associated with the higher altitude.

(In this connection, it should be noted that a standard lapse rate of about 0.002° C per foot is assumed throughout the calculations. In actuality, true average lapse rates tend to be somewhat lower when ground temperatures are lower, and it follows that the air temperatures at

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altitude used in these calculations are somewhat lower than they should be at, for example, a sea-level temperature of 0° C. However, the adoption of a variable lapse rate would have greatly complicated both presentation and possible utilization of the results without significantly contributing to the overall accuracy and generality of the study.)

In general, it is indicated in figure 5 that large increases of distance of fall for fixed mass losses occur with increasing starting altitude, ground temperature remaining the same. This effect does not vary rapidly with droplet size. As an example, at 30° C the calculated distances of fall for a mass loss of 25 percent are 215 and 589 feet for a 500-micron droplet falling from altitudes of 5000 and 13,000 feet, respectively; the corresponding figures for a 2000-micron droplet are 3110 and 6663 feet. Thus, an increase of about 174 percent between the two altitudes occurs for the 500-micron droplet, and an increase of about 114 percent occurs for the 2000-micron droplet. This effect (the spread between the increase percentages for the two droplet sizes) is more marked at the higher mass losses, but is never large.

In figure 6, total fractional mass losses are plotted as a function of temperature for JP-1 and JP-4 droplets of both 500- and 1000-micron diameters for a fixed distance of fall (1000 ft) from a starting altitude of 3000 feet. The variations with temperature of mean mass loss rate during such a fall are seen to be great for the four fuel-droplet size combinations. However, the rate of increase of mean loss rate with temperature is lower for JP-1 at the lower air temperatures than for JP-4, whereas the opposite is true at air temperatures above about 0° C for 500-micron droplets and above about 25° C for 1000-micron droplets. These results would, of course, be different for different selections of droplet size, initial altitude, and distance of fall. Nevertheless, it is evident that mean evaporation rates of JP-1 droplets at a given temperature and of JP-4 droplets at a temperature about 20° C lower are about equal if relatively small distances of fall and ordinary temperatures are considered.

It is indicated in reference 2 that droplets having diameters in the vicinity of 500 microns will probably make the largest contributions to total liquid droplet concentrations. Considering, then, only the 500-micron results exhibited in figure 6, the following summarizes what may be designated working relations among total mass losses for the two fuels at various temperatures: For JP-1 droplets falling in air at temperatures between about -10° and 20° C, total evaporation losses may be estimated by using calculated results for JP-4 at temperatures about 20° C lower. This decrement will be somewhat too large at the higher air temperatures, and several degrees too small at the lower temperatures. For JP-4 droplets falling in air at temperatures roughly between -40° and 10° C, total evaporation losses may be estimated by using calculated results for JP-1

at temperatures about 20° C higher. As in the converse case, this increment will be several degrees too large at the higher temperatures, and several degrees too low at the lower temperatures.

CONCLUDING REMARKS

It was indicated in previous reports (refs. 1 and 2) that, even when JP-4 is jettisoned at as small a ground clearance as 500 feet, dangerous airborne fuel concentrations (flammability being the sole criterion) would seldom, if ever, occur near the ground. The conclusion was valid even at air temperatures so low (less than -15° C for JP-4) that little evaporation of liquid fuel droplets would occur. Clearly, that conclusion requires no modification in the case of JP-1.

However, more liquid JP-1 will reach ground level than JP-4 under otherwise identical circumstances at all except very low or very high temperatures in view of the much lower mean rates of evaporation of JP-1 droplets at ordinary temperatures. It follows that, where ground contamination is a potential hazard or would otherwise constitute a nuisance, low-altitude jettisoning of JP-1 will be more objectionable than such jettisoning of JP-4.

More specifically, the results of this study indicate that for small or moderate distances of fall little or no JP-1 fuel in droplet form will evaporate when the sea-level air temperature is 0° C or less, that evaporation rates remain low at temperatures between 0° and 10° C, and that in general the evaporative behavior of JP-1 is comparable at a given temperature with that of JP-4 (ref. 1) at a temperature about 20° C lower. Accordingly, dispersal or ground contamination calculations made for either fuel will be approximately applicable to the other fuel when due allowance for this 20° C differential has been made. Such a procedure would not, however, be valid at very high or very low temperatures.

Lewis Research Center
    National Aeronautics and Space Administration
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APPENDIX A

REVISED COMPUTER PROGRAM

The analytical approach to the problem of the free fall and evapora-
tion of fuel droplets consisting of mixtures of many hydrocarbons was
discussed in some detail in reference 1. For the present work, a com-
pletely rewritten program was developed and coded for a faster computer.
The analytical foundation, however, was not altered. Accordingly, only
nontrivial differences between the original and present treatments are
discussed; derivations of all major equations common to the two programs
are given in reference 1.

Two principal changes have been incorporated. First, the accuracy
of the results has been increased by taking into account the lowering
of droplet temperature as the result of evaporation. A heat-balance
relation, together with appropriate program logic, now provides for such
droplet cooling regardless of the magnitude of that effect. The second
major change was the elimination of the approximation (eqs. (B4) to (B7)
of ref. 1) previously made that droplet falling speed and relative Reynolds
number are dependent only on droplet diameter (the droplet density remain-
ing the same) at low altitudes. In the present program, the function φ,
the droplet Reynolds number, and the droplet falling speed are now com-
puted at each step in the calculation procedure in accordance with re-
lations (B1) to (B3) and (B8) to (B12) of reference 1. Accordingly,
variations of all relevant atmosphere properties are at all times taken
into account. In this connection, a further refinement in the present
program, although a minor one, is the calculation of the correct droplet
density at all times; changes of composition as well as droplet con-
traction and expansion with temperature variations are considered.

An additional minor analytical change was the substitution of a mean
Schmidt number averaged over all fuel components for one averaged (as in
ref. 1) over only the three components that evaporate most rapidly. It
was felt that, in general, such an average would be more nearly repre-
sentative of mean conditions during the evaporative history of the drop-
let. Finally, a fixed Schmidt number is no longer used; the Schmidt
number is permitted to vary with air viscosity and density.

In addition to the analytical changes just mentioned, a number of
improvements in program strategy were made which materially expedite
the calculations without compromising accuracy. The most important of
these is the provision for automatic selection of the magnitude of the
time step. At each step in the program, the magnitudes of the fractional
mass change and the change in altitude are examined. If both are un-
necessarily small, the time step is doubled. If both are becoming too
large, the time step is halved. In either case, the step just executed

is repeated at the new stop size to maintain accuracy. Appropriate quadratic extrapolation relations are used for several of the major variables to facilitate computer transition from "guesses" to acceptable iterates. Regardless of the magnitude of the time step, the rate of release by the computer of calculated results (punchout) is independently and automatically controlled so as to insure release of an optimum amount of information. Finally, if the rate of evaporation of the droplet at any time falls to a prespecified very low value, the portion of the program that performs the evaporation calculations is automatically bypassed; the droplet continues to fall to the ground without change of mass or composition, and program execution is greatly accelerated.

The complete computer program is presented in figure 7 in block form. Numbers in parentheses within the blocks are references to correspondingly numbered equations (or groups of equations) as given in this appendix. A complete list of the symbols used (altered trivially from those of ref. 1) is given in appendix B. The only important relations not present in reference 1 are the heat-balance equation (31) and the auxiliary relations (eqs. (15), (29), and (30)) required for the determination of the heat-transfer coefficient. Values of various program constants are given at the end of this appendix. The properties of the (assumed) components of JP-1 fuel, as obtained from references 3 and 4, are given in table II.

Equations

Note: All summations are extended over the ten components. Accordingly, $\sum_{1}^{10}$ should be understood wherever $\sum$ appears. Subscripts +1 or 0 are occasionally omitted where their presence would merely complicate a relation without adding meaning, for example, as in equations (30) and (31).

$$C_{13,i} = -7.7702702(NBP)_i$$

$$V_{in} = \frac{\pi}{6} D_{in}^3$$

$$K_a = 0.1 \sum \rho_i$$

$$m_i = 0.1 \, V_{in}\rho_i(1 + K_b t_d)$$

$$V_{c,in} = \frac{M_i e_i}{\rho_i}$$

$$\beta_{n,i} = \frac{\sqrt{\frac{1}{M_i} + \frac{1}{M_a}}}{\left(V_{c,i}^{1/3} + V_{c,a}^{1/3}\right)^2} \frac{(0.004215)273.16^{3/2}}{1.0}$$

$$\beta_m = 0.1 \sum \beta_{n,i}$$

$$K_{p,i} = \log_{10} \frac{(NBP)_{ref}}{(NBP)_i} C_{15} - 28.03809$$

$$T_s = t_s + 273.16$$

$$\rho_s = 0.353/T_s$$

$$T_{a,in} = T_s - aH_n$$

$$t_{a,in} = T_{a,in} - 273.16$$

$$\left.\vphantom{\begin{array}{c}1\\1\\1\\1\\1\\1\\1\\1\\1\\1\\1\\1\\1\end{array}}\right\} \quad (1)$$

$$\rho_{d,in} = K_a(1 + K_b t_d)$$

$$m_{d,in} = \rho_{d,in} V_{in}$$

$$\left.\vphantom{\begin{array}{c}1\\1\end{array}}\right\} \quad (2)$$

$$\overline{T}_a = T_s - a\overline{H}$$

$$\overline{t}_a = \overline{T}_a - 273.16$$

$$\overline{T}_a^* = 1.8 \, \overline{T}_a$$

$$\overline{\rho}_a = \rho_s(\overline{T}_a/T_s)^{4.2561}$$

$$\left.\vphantom{\begin{array}{c}1\\1\\1\\1\end{array}}\right\} \quad (3)$$

$$t_d = T_d - 273.16 \tag{4}$$

$$\rho_d = m_d/V_d \tag{5}$$

$$\overline{\mu}_a = K_c + \overline{t}_a(K_d - K_e\overline{t}_a) \tag{6}$$

$$\varphi = (32/3)(\overline{\rho}_d\overline{\rho}_a g/\overline{\mu}^2)(\overline{D}_d/2)^3 \tag{7}$$

$$\overline{Re}_t = 10^{-K_f + \log_{10}\overline{\varphi}(K_g - K_h\log_{10}\varphi)} \tag{8}$$

$$\overline{U}_t = 0.032808\ \overline{\mu}_a\overline{Re}_t/\overline{D}_d\overline{\rho}_a \tag{9}$$

$$\Delta H = \overline{U}_t\Delta\theta \tag{10}$$

$$\delta_H = \left|\frac{\Delta H - \Delta H_g}{\Delta H}\right| - 0.001 \tag{11}$$

$(\delta_H \geq 0?)$

$$H_0 + \Delta H_{+1} = H_{+1} \tag{12}$$

$$Sc = \overline{\mu}_a/\overline{\rho}_a\beta_m \tag{13}$$

$$\overline{Nu}_m = K_i + K_j\ Sc^{1/3}\ \overline{Re}_t^{1/2} \tag{14}$$

$$\overline{Nu}_h = K_i + K_j\ Pr^{1/3}\ \overline{Re}_t^{1/2} \tag{15}$$

$$\overline{P}_a = P_n(\overline{T}_a/T_n)^{5.2561} \tag{16}$$

$$\overline{h}_{m,i} = \left(\frac{\overline{Nu}_m\overline{T}_a^{0.75}}{\overline{D}_d\overline{P}_a}\right)\beta_{n,i}m_iK_3 \tag{17}$$

$$\alpha_i = m_i/M_i \tag{18}$$

$$\alpha_d = \sum \alpha_i \tag{19}$$

$$\epsilon_i = \alpha_i/\alpha_T \tag{20}$$

$$\overline{p}_i = 10^{\left[(c_{13,i}(\overline{T}_d)^{-1}c_{15}\log_{10}\overline{T}_d) - K_{p,i}\right]} \tag{21}$$

$$(\Delta m_i)_0 = \pi \overline{h}_{m,i} \overline{D}_d^2 \, \overline{p}_i \epsilon_i (NP) \Delta\theta \tag{22}$$

$$m_i = m_{i,-1} - (\Delta m_i)_0 \tag{23}$$

$$V_i = m_i/\rho_i \tag{24}$$

$$V_d = (1 + K_b \overline{t}_d)^{-1} \sum V_i \tag{25}$$

$$m_{d,+1} = \sum m_i \tag{26}$$

$$M_m = m_d^{-1} \sum m_i M_i \tag{27}$$

$$(\Delta m_d)_{+1} = m_{d,-1} - m_{d,+1} \tag{28}$$

$$\text{Total heat of vaporization} = \lambda \sum (\Delta m_d)_{+1} \tag{29}$$

$$\left. \begin{aligned} \overline{k}_a &= k_l + k_m \overline{t}_a \\ \overline{h}_h &= \overline{k}_a \overline{Nu}_h / \overline{D}_d \end{aligned} \right\} \tag{30}$$

$$\overline{T}_d = \overline{T}_a - \left[(\text{total heat of vaporization}) / \pi \overline{D}_d^2 \, \overline{h}_h \Delta\theta \right] \tag{31}$$

$$(\Delta T_d)_H = T_{d,-1} - T_{d,+1} \tag{32}$$

$$\delta_T \equiv 0.1 - \left| (\Delta T_d)_{+1} - (\Delta T_d)_0 \right| \tag{33}$$

$(\delta_T \geq 0?;$ test constant subject to operator choice; here 0.1)

$$\delta_m \equiv 0.001 - \left| \frac{m_{d,+1} - m_{d,0}}{\overline{D}_d} \right| \tag{34}$$

$(\delta_m \geq 0?;$ test constant subject to operator choice; here 0.001)

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$$x_0(\text{new value}) = \frac{\alpha^* x_{+1} + x_0(\text{existing})}{\alpha^* + 1} \tag{35}$$

(α^* subject to operator choice; generally 0.5 or 0.75)

$$\delta_E \equiv 10^{-6} - \left| \frac{\Delta D_d}{D_d \Delta H} \right| \tag{36}$$

($\delta_E \geq 0$?; test constant subject to operator choice; here 10^{-6})

$$\delta_{m,1} \equiv K_{\Delta 1} - \frac{\Delta m}{m_0} \quad \underline{\text{or}} \quad K_{\Delta 1} - \frac{2 \Delta m}{m_0} \tag{37}$$

($\delta_{m,1} \geq 0$?)

$$\delta_H \equiv K_{\Delta 2} - \Delta H \quad \underline{\text{or}} \quad K_{\Delta 2} - 2\Delta H \tag{38}$$

($\delta_H \geq 0$?)

$$\Delta H = 6(\Delta H)_0 - 8(\Delta H)_{-1} + 3(\Delta H)_{-2} \tag{39}$$

(Corresponding relations for D, ΔT, Δm)

$$\Delta H = 3(\Delta H)_0 - 3(\Delta H)_{-1} + (\Delta H)_{-2} \tag{40}$$

(Corresponding relations for D, ΔT, Δm)

Constants

a 0.0019812 °C ft^{-1}

C_{15} 7.0274130 nondimensional

K_b -0.00098594 (°C)$^{-1}$

K_c 0.0001718 poise

K_d 5.08×10^{-7} poise (°C)$^{-1}$

K_e 4.93×10^{-10} poise (°C)$^{-2}$

K_f 1.35134 nondimensional

K_g 1.02468 nondimensional

K_h 0.046399 nondimensional

K_i 2.0 nondimensional

K_j 0.55 nondimensional

K_3 6.63984×10^{-7} $cm^{-3} mole^{-1} (^\circ K)^{-0.75}$

$K_{\triangle 1}$ 0.01667 nondimensional

$K_{\triangle 2}$ 100 ft

k_l 2404.4 erg $cm^{-1} sec^{-1} (^\circ C)^{-1}$

k_m 7.085 erg $cm^{-1} sec^{-1} (^\circ C)^{-2}$

R 8.31436×10^7 erg $mole^{-1} (^\circ K)^{-1}$

$V_{c,a}$ 31.4797 cm^3

λ 3.60×10^9 erg g^{-1}

APPENDIX B

SYMBOLS

(Units, where not indicated, are those required by relation in which symbol is used. Abbreviation "n.d." denotes nondimensional.)

a lapse rate, $^{\circ}C$ ft^{-1}

C_{13} constant defined by equation (1), $^{\circ}R$

C_{15} constant in equation (21)

D diameter, cm

e expansion factor, $(^{\circ}C)^{-1}$

g gravitational force, dyne g^{-1}

H altitude, ft

h_h heat-transfer coefficient, erg $cm^{-2}sec^{-1}(^{\circ}C)^{-1}$

h_m mass-transfer coefficient, $(g\ cm^{-2}sec^{-1})/(dyne\ cm^{-2})$

K_a initial droplet density at 0° C (assuming all partial volumes = 0.1), $g\ cm^{-3}$

K_b fractional change of droplet density per unit temperature change (assuming equality of all component coefficients of expansion), $(^{\circ}C)^{-1}$

K_c constant in equation (6), poise

K_d constant in equation (6), poise $(^{\circ}C)^{-1}$

K_e constant in equation (6), poise $(^{\circ}C)^{-2}$

K_f,K_g,K_h constants in equation (8), n.d.

K_i,K_j constants in equations (14) and (15), n.d.

K_p constant (for a given component) in equations (1) and (21)

K_3 constant in equation (17), $cm^{-3}mole^{-1}(^{\circ}K)^{-0.75}$

$K_{\Delta 1}$ test constant in equation (37), n.d.

$K_{\triangle 2}$	test constant in equation (38), ft
k_a	thermal conductivity of air, $erg\ cm^{-1}sec^{-1}(^\circ C)^{-1}$
k_l	constant in equations group (30), $erg\ cm^{-1}sec^{-1}(^\circ C)^{-1}$
k_m	constant in equations group (30), $erg\ cm^{-1}sec^{-1}(^\circ C)^{-2}$
M	molecular weight, $g\ mole^{-1}$
m	mass, g
NBP	normal boiling point, $^\circ R$
NP	1,013,250 $dyne\ cm^{-2}\ atm^{-1}$ (conversion factor for p)
Nu_h	heat-transfer Nusselt number, n.d.
Nu_m	mass-transfer Nusselt number, n.d.
P	pressure (ambient), $dyne\ cm^{-2}$
Pr	Prandtl number, n.d.
p	vapor pressure, atm
Re	Reynolds number, n.d.
Sc	Schmidt number, n.d.
T	temperature, $^\circ K$
T*	temperature, $^\circ R$
t	temperature, $^\circ C$
U	droplet falling speed, $ft\ sec^{-1}$
V	volume, cm^3
x	any variable
α	number of moles
$\alpha *$	weighting factor; units those of x^{-1}
β	diffusion coefficient, $cm^2\ sec^{-1}$

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Δ	increment
δ	small difference
ϵ	fractional molality, n.d.
θ	time, sec
λ	heat of vaporization, erg g^{-1}
μ	viscosity, poises
ρ	density, g cm^{-3}
φ	variable defined by equation (B7), n.d.

Subscripts:

(Note: When not listed here, see subscripted symbol.)

a	pertaining to air (exceptions: see symbols K_a and k_a)
c	characteristic value (as in V_c, the characteristic volume)
d	pertaining to entire droplet (exception: see symbol K_d)
g	estimated ("guessed") value (exception: see symbol K_g)
h	heat transfer (exception: see symbol K_h)
i	pertaining to a component i (exception: see symbol K_i)
in	initial value
m	weight-averaged mean (overall components; exceptions: see symbols h_m, k_m, and Nu_m)
n	under normal conditions (0° C, 1 atm pressure)
ref	reference value
s	sea-level value
t	terminal value
-2,-1,0	values at various stages of calculation; "0" denotes current value, "-1" preceding value, etc.
+1	tentative current value

Superscript:

  —   denotes value that is a representative mean over a finite
      time step (as, e.g., $\overline{H}$ or $\overline{D}$)

REFERENCES

1. Lowell, Herman H.: Free Fall and Evaporation of JP-4 Jet Fuel Drop-
  lets in a Quiet Atmosphere. NASA TN D-33, 1959.

2. Lowell, Herman H.: Dispersion of Jettisoned JP-4 Fuel by Atmospheric
  Turbulence, Evaporation, and Varying Rates of Fall of Free Droplets.
  NASA TN D-84, 1959.

3. Barnett, Henry C., and Hibbard, Robert R.: Properties of Aircraft
  Fuels. NACA TN 3276, 1956.

4. Maxwell, J. B.: Data Book on Hydrocarbons. Second ed.,
  D. Van Nostrand Co., Inc., 1951.

TABLE I. - PARAMETER COMBINATIONS FOR WHICH RESULTS

ARE PLOTTED IN FIGURES 1, 2, 3, AND 4

Starting altitude, ft	Droplet size, microns	Figure number					
		Sea-level air temperature, °C					
		-30	-15	0	15	30	45
3,000	250	1,3	1,3	1,3	1,3	1,3	1,3
	500	[a]1					1,3
	750	[a]1	↓	↓	↓	↓	
	1000	(b)				↓	1,3
	1500	[a]1				3	
	2000	[a]1	1,[c]3	↓	↓	1,3	1,3
5,000	250	[a]1		1,3		1,3	1,3
	500	[a]1		1,3		1,3	
	750	[a]1		1,2,3,4		1,2,3,4	1,3
	1000	[a]1		1,3		1,3	
	1500	[a]1		1,3		1,3	
	2000	[a]1		1,2,3,4		1,2,3,4	
7,000	500	[a]1		1,3		1,3	
	1000			3		3	
	2000	[a]1		1,3		1,3	
9,000	500	[a]1		1		1	
	2000	[a]1		1		1	
11,000	500			1			
	2000			1			
13,000	500			1			
	2000			1			

[a]No evaporation permitted during calculation.

[b]Results not available.

[c]Horizontal straight line.

TABLE II. - PROPERTIES OF COMPONENTS OF ASSUMED MIXTURE[a]

Component	Percent evaporated at which evaluated	Mean boiling point, ^{O}F	Molecular weight, M_i, g/mole	Density		Expansion factor (b)
				^{O}API	ρ_i, g/cm^3	
1	5	337	135	43.4	0.809	1.1685
2	15	350	139	42.3	.814	1.175
3	25	358	142	41.3	.819	1.179
4	35	361	142.5	41.1	.820	1.1805
5	45	366	144	40.7	.822	1.183
6	55	373	146.5	40.0	.825	1.1865
7	65	379	148	39.7	.8265	1.1895
8	75	389	151.5	38.9	.830	1.1945
9	85	402	156	37.8	.836	1.201
10	95	425	164	36.2	.844	1.2125

[a]Volume average boiling point, 374.0^{O} F (same as that of Barnett and Hibbard, ref. 3).
Mean average boiling point, 377° F.
Group V plot average of ref. 4 (p. 22) used; characterization factor is 11.6.

[b]Ratio of density at room temperature to density at boiling point.
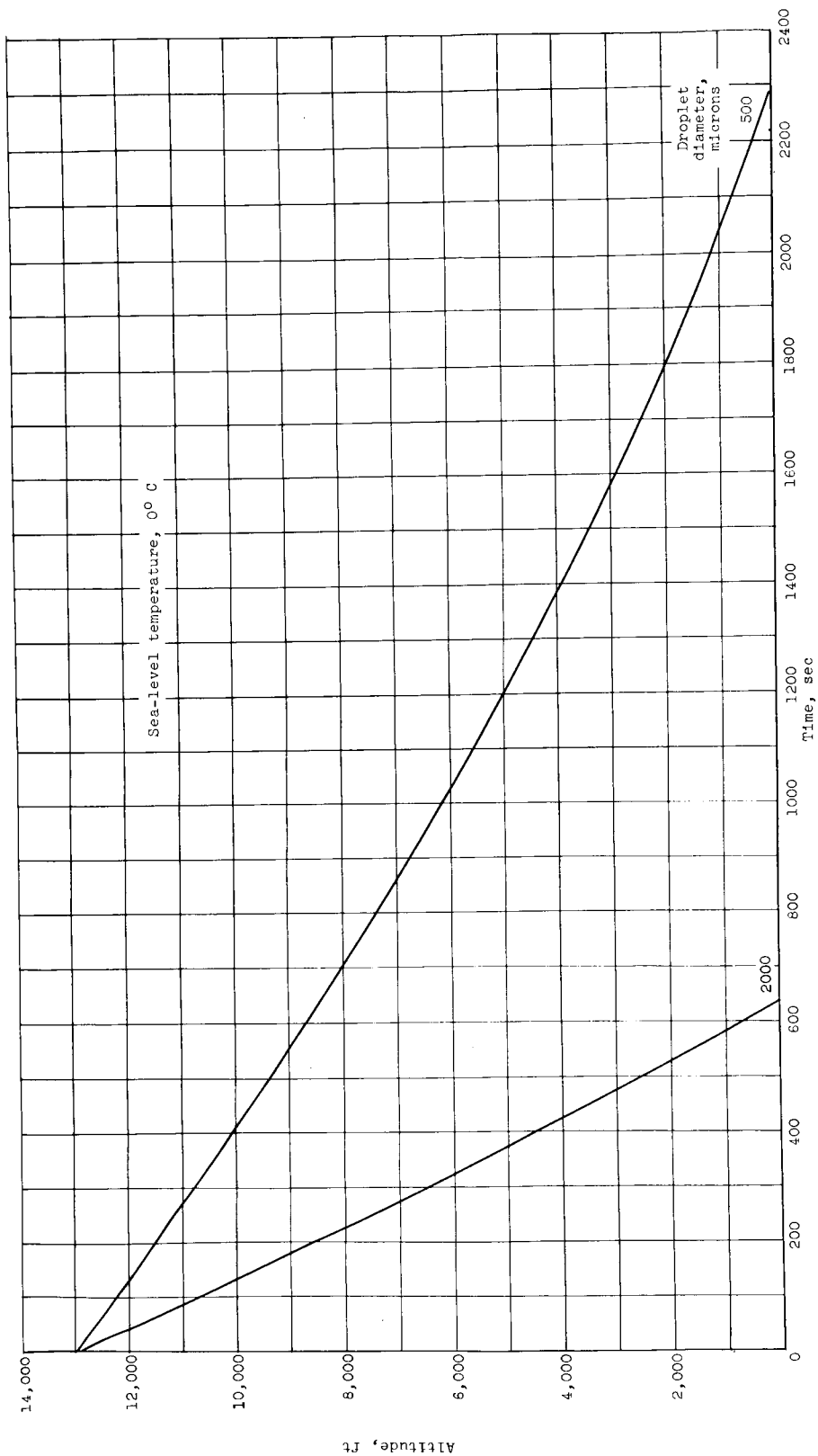
(a) Starting altitude, 13,000 feet.

Figure 1. - Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.
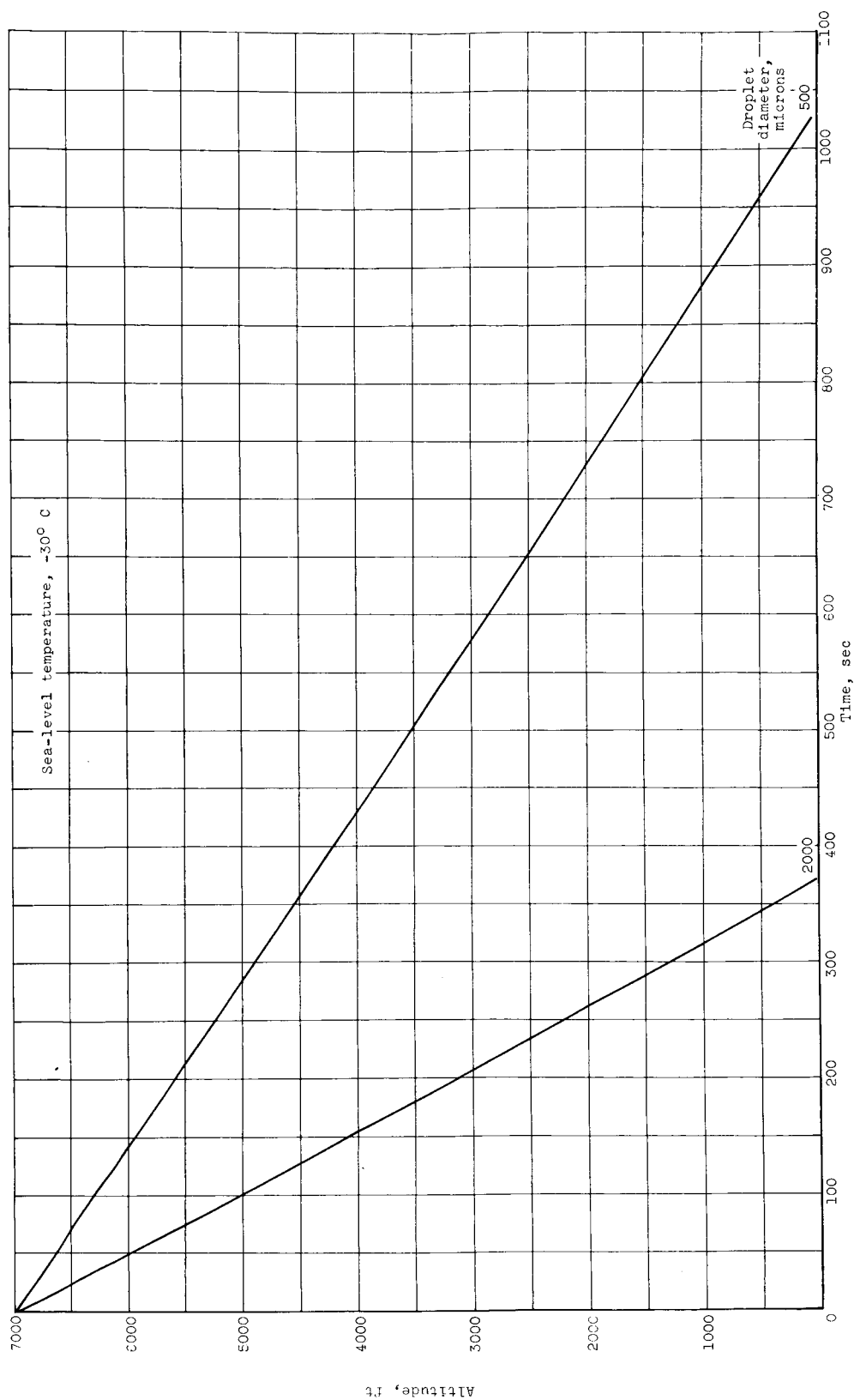
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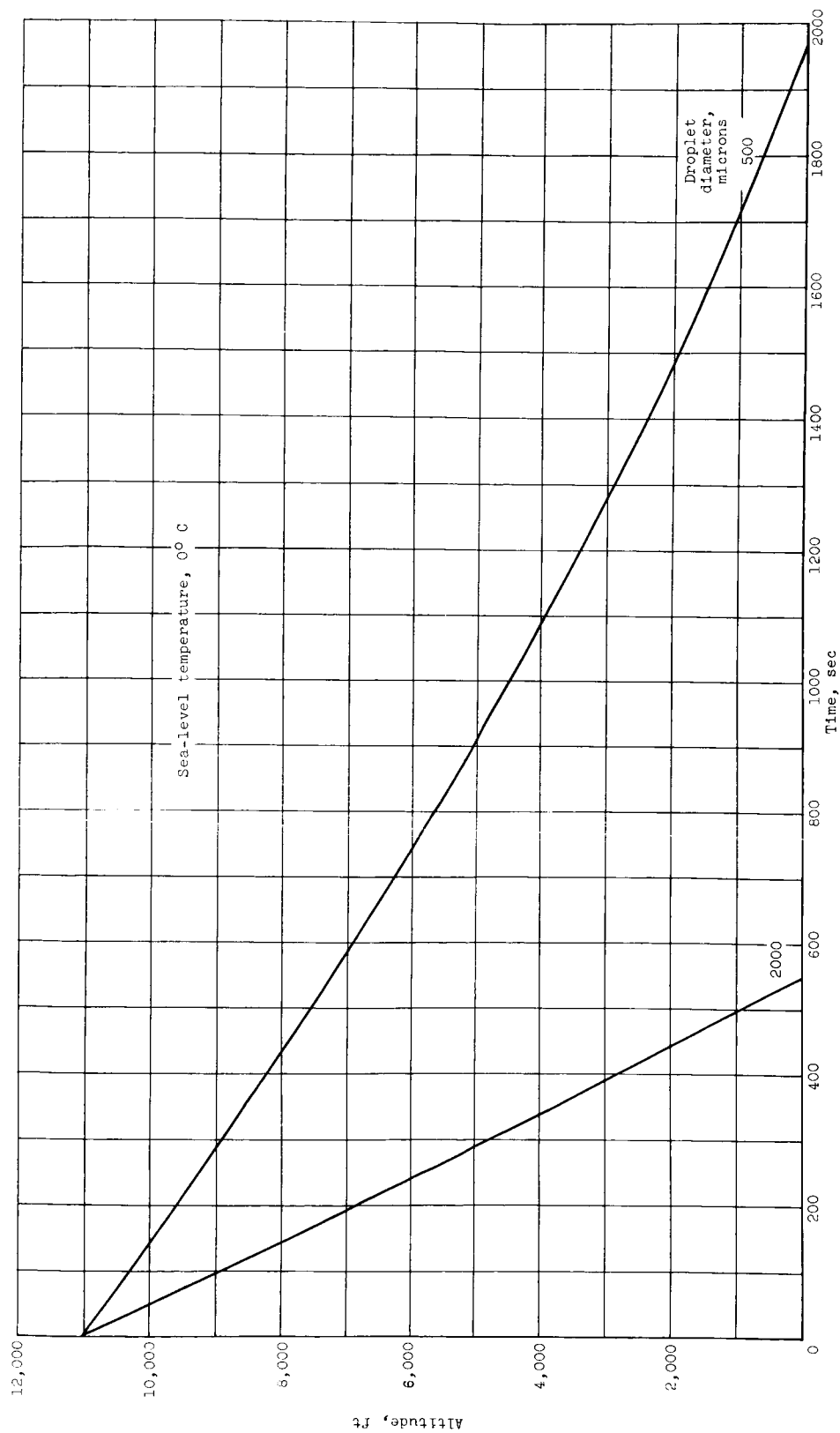
(b) Starting altitude, 11,000 feet.

Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.
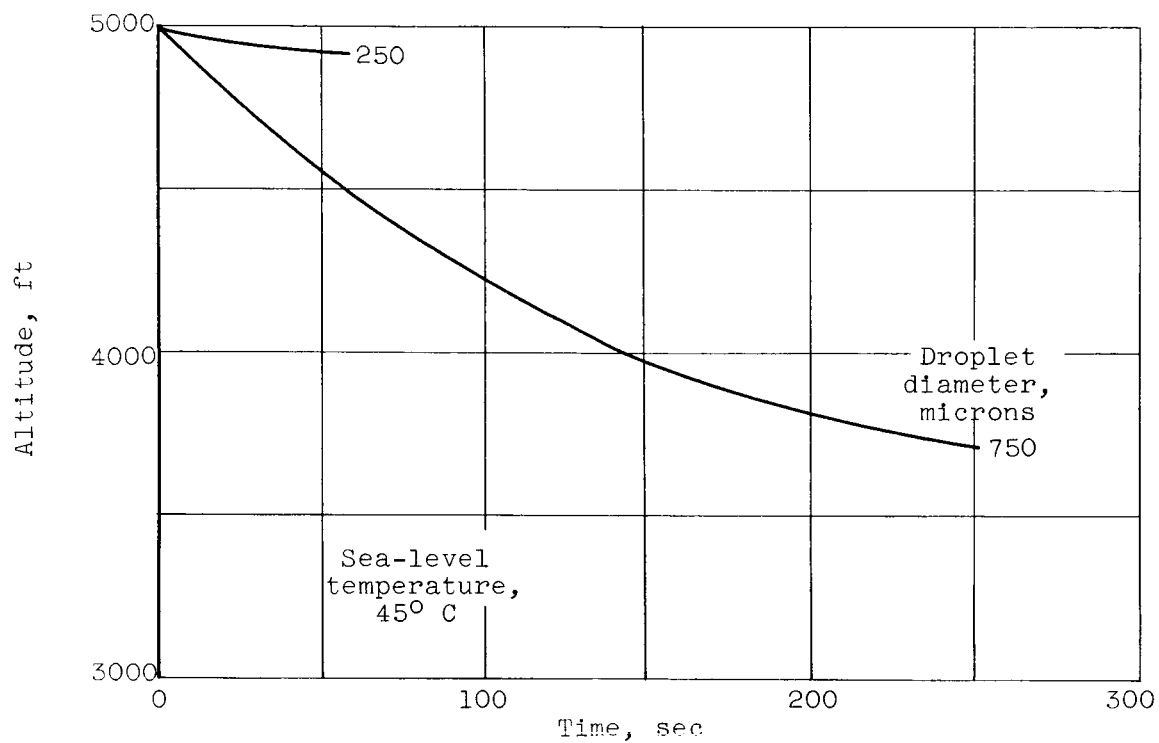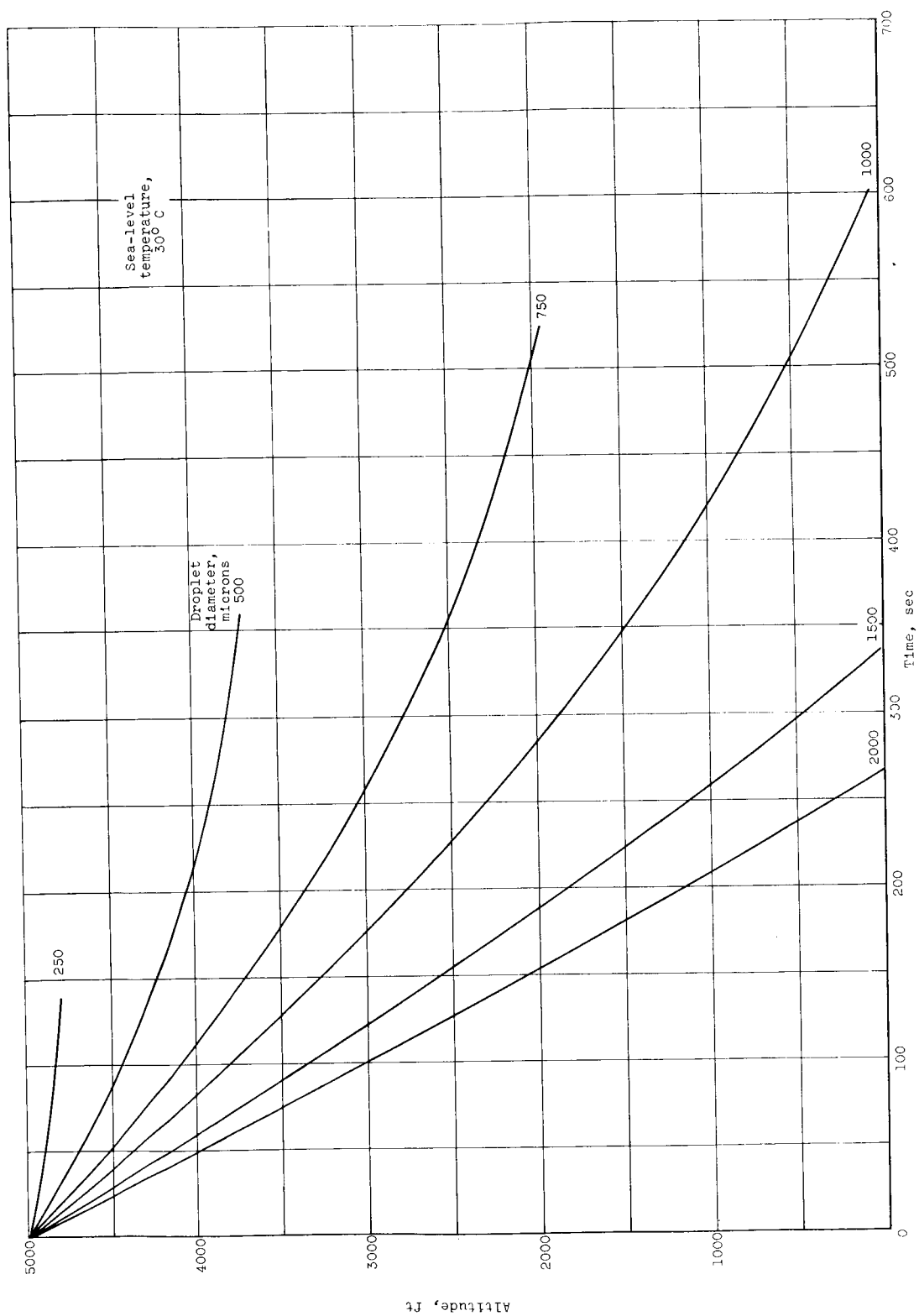
24
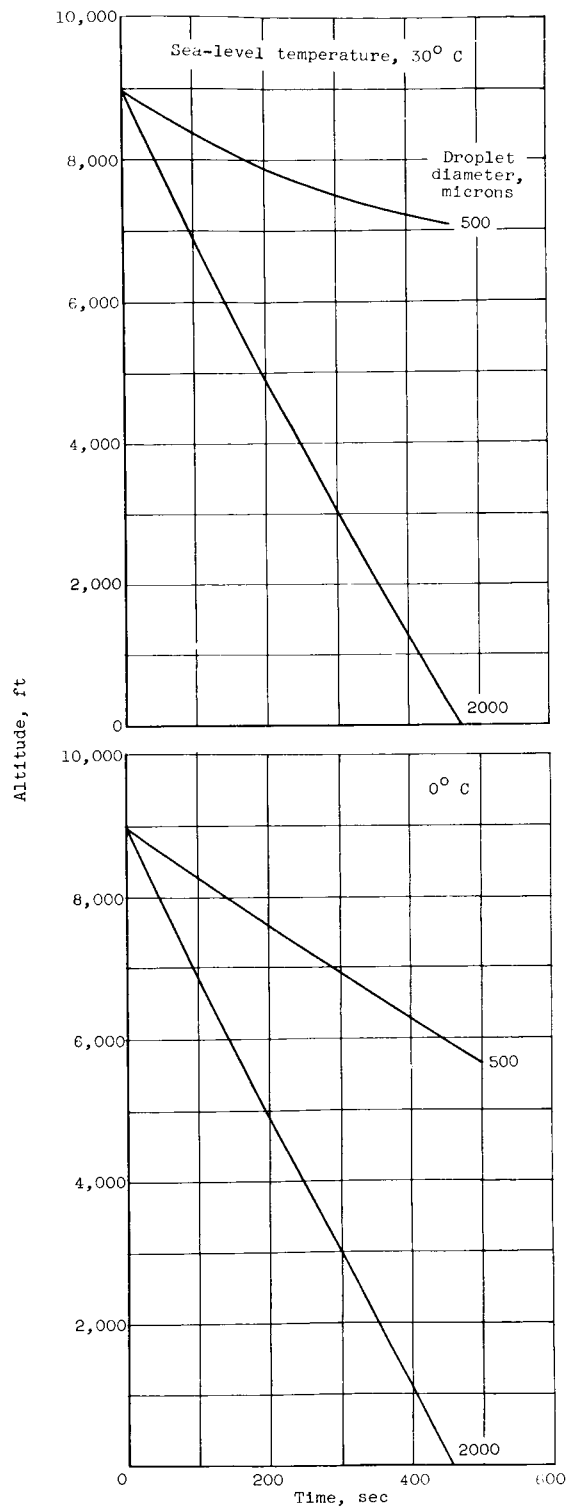
(c) Starting altitude, 9000 feet.

Figure 1. - Continued. Droplet altitude
as function of time after release at
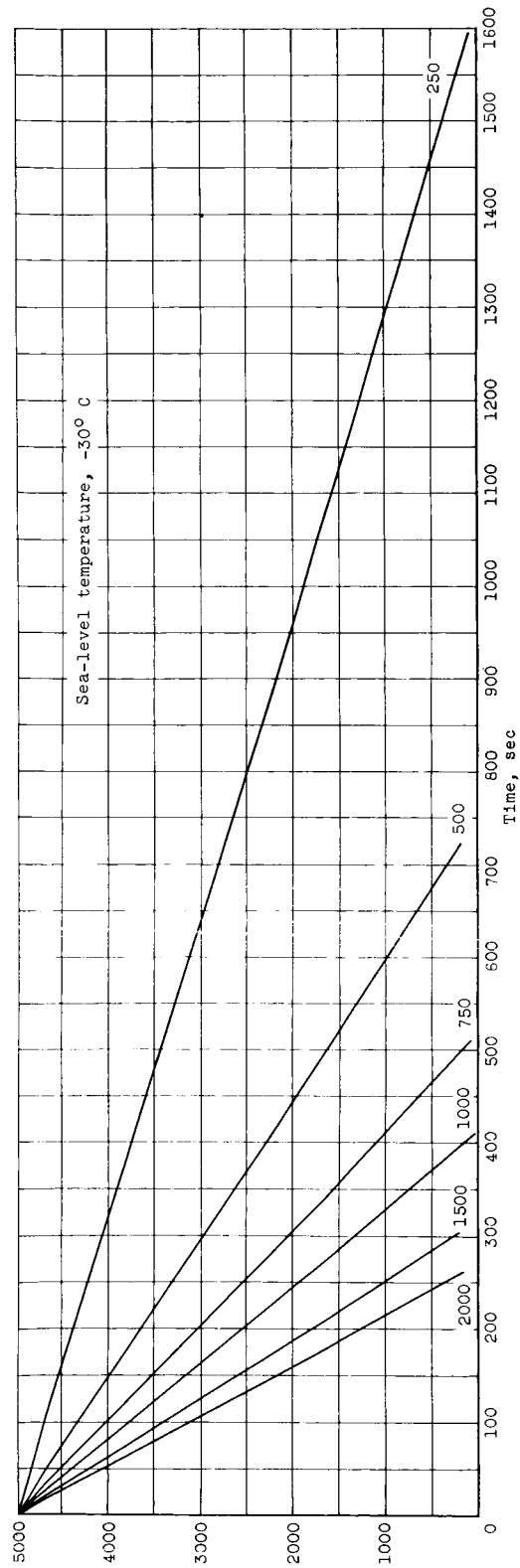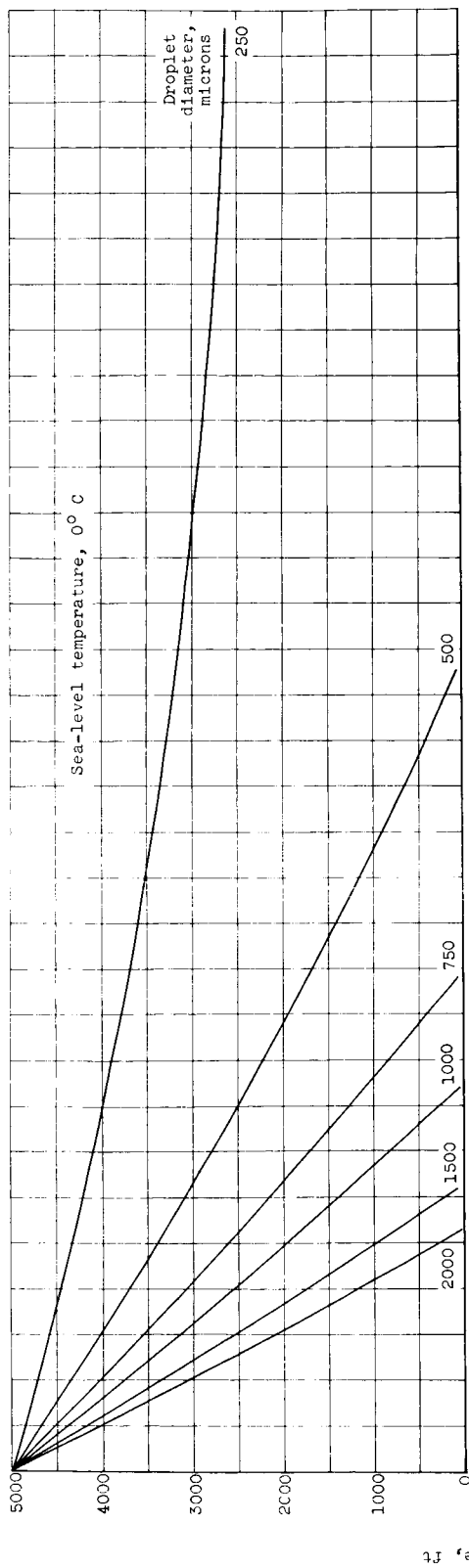fixed sea-level air temperatures. Fuel,
JP-1.
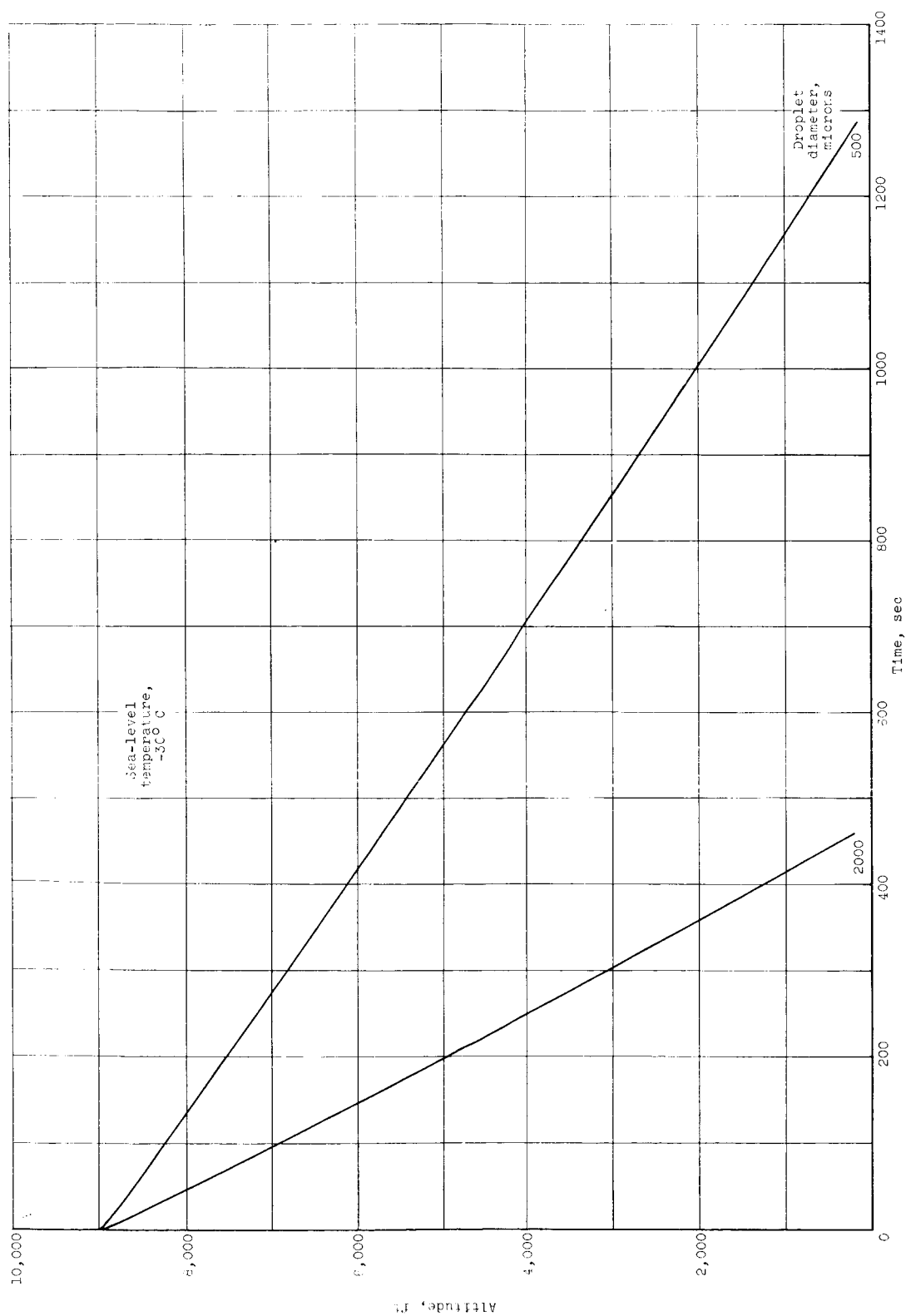
(c) Concluded. Starting altitude, 9000 feet.

Figure 1. – Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.

(d) Starting altitude, 7000 feet.

Figure 1. – Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.

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CN-4 back
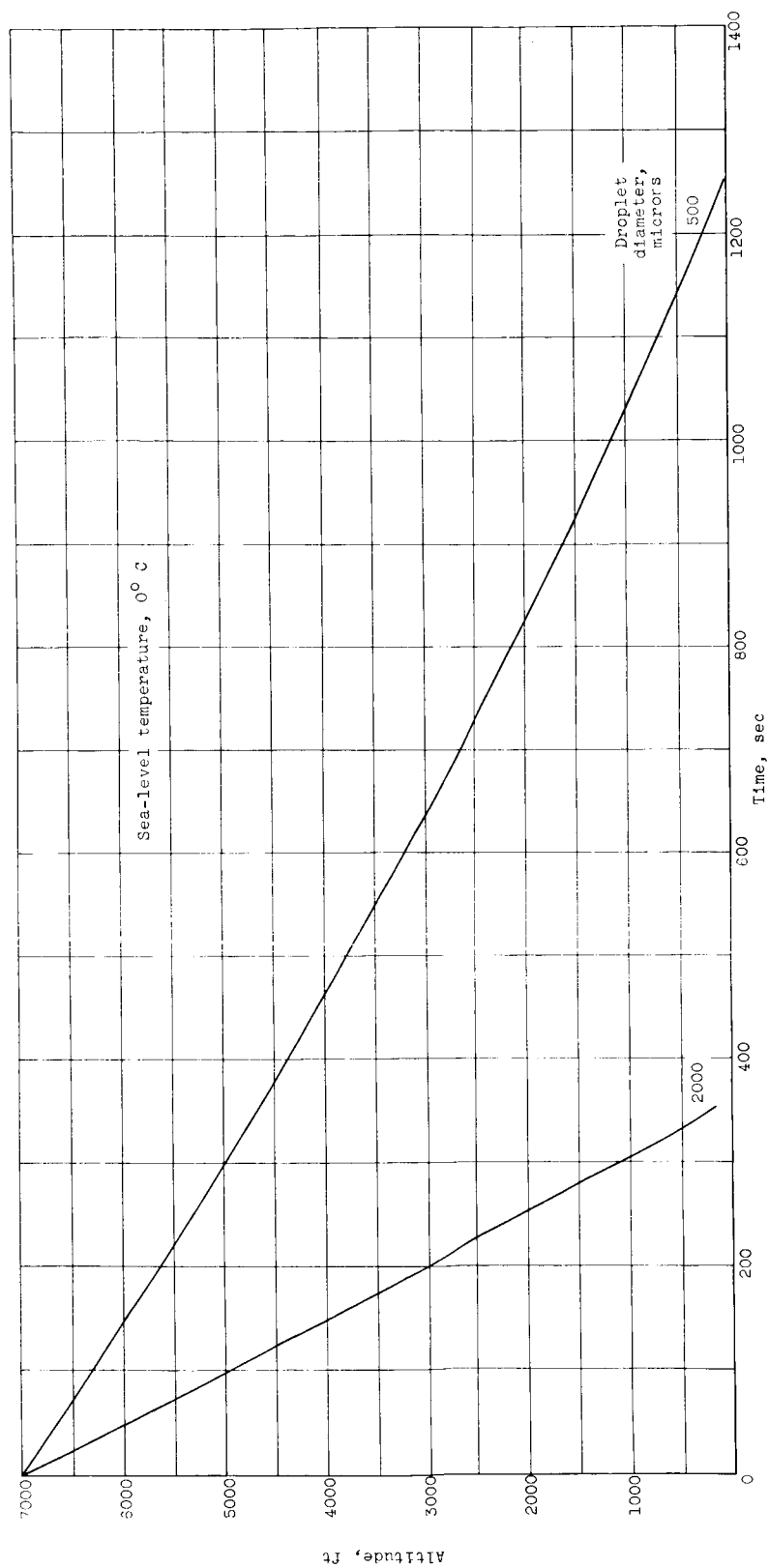
(d) Continued. Starting altitude, 7000 feet.

Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.
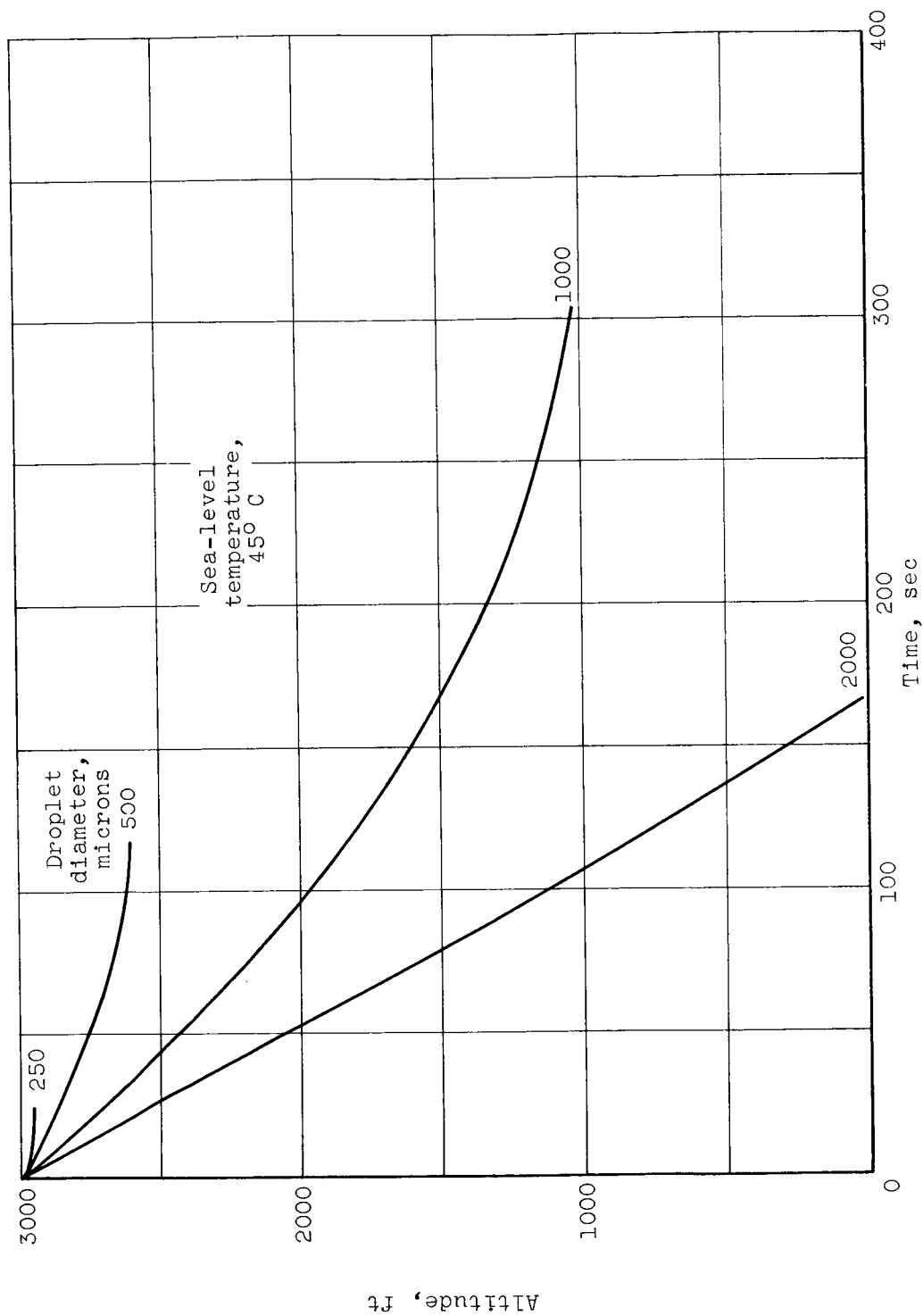
(d) Concluded. Starting altitude, 7000 feet.

Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.

(e) Starting altitude, 5000 feet.

Figure 1. – Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.

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(e) Continued. Starting altitude, 5000 feet.

Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.
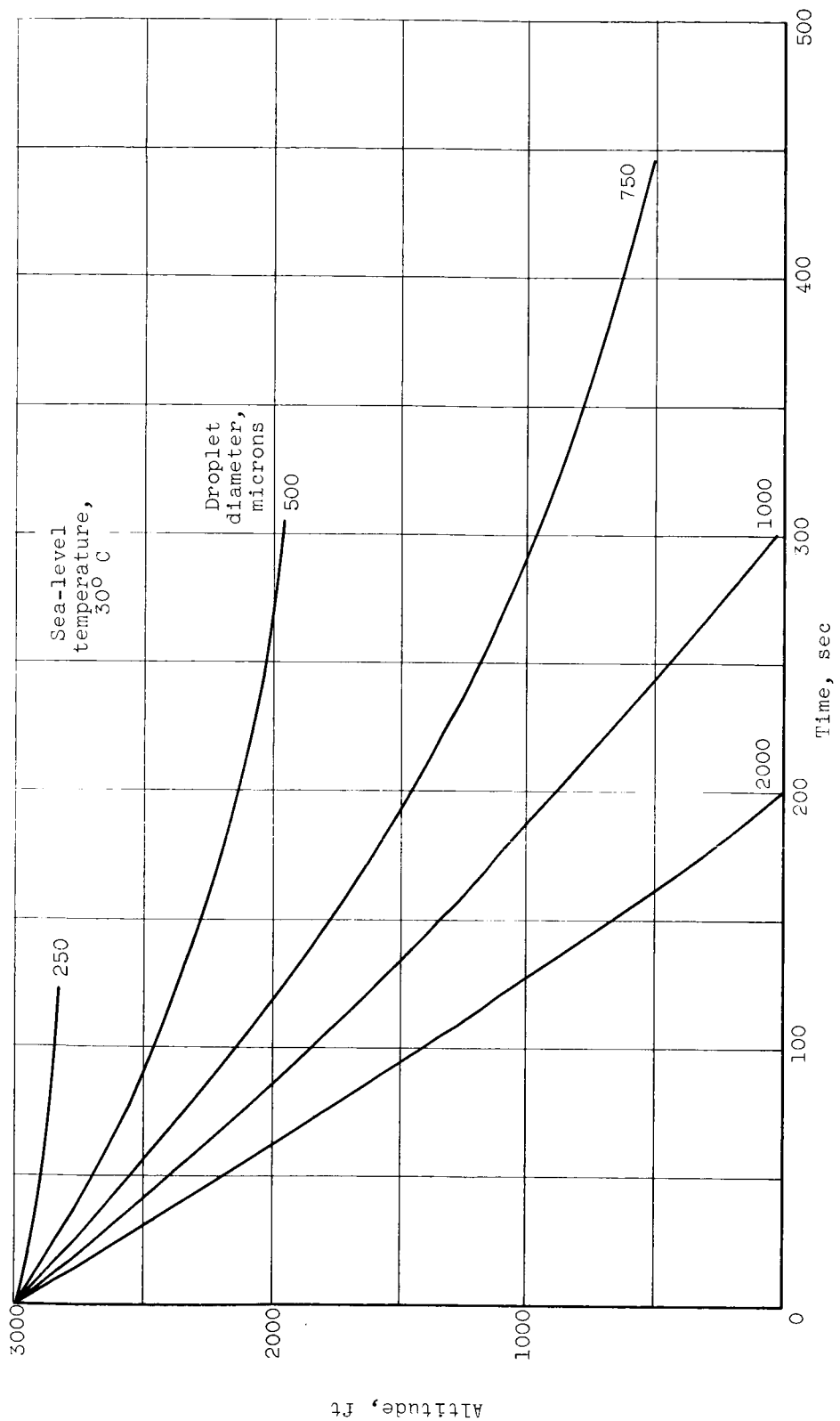
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(e) Concluded. Starting altitude, 5000 feet.

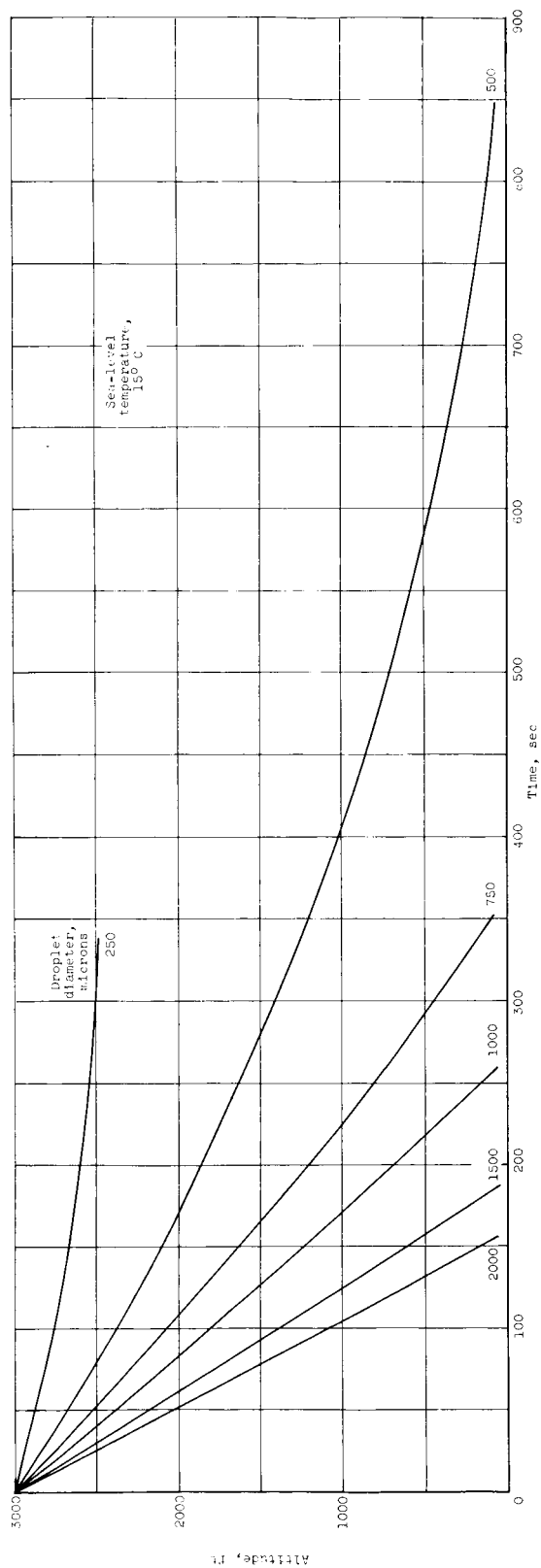Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures.

(f) Starting altitude, 3000 feet.

Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.

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(f) Continued. Starting altitude, 3000 feet.

Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.

(f) Continued. Starting altitude, 3000 feet.

Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.

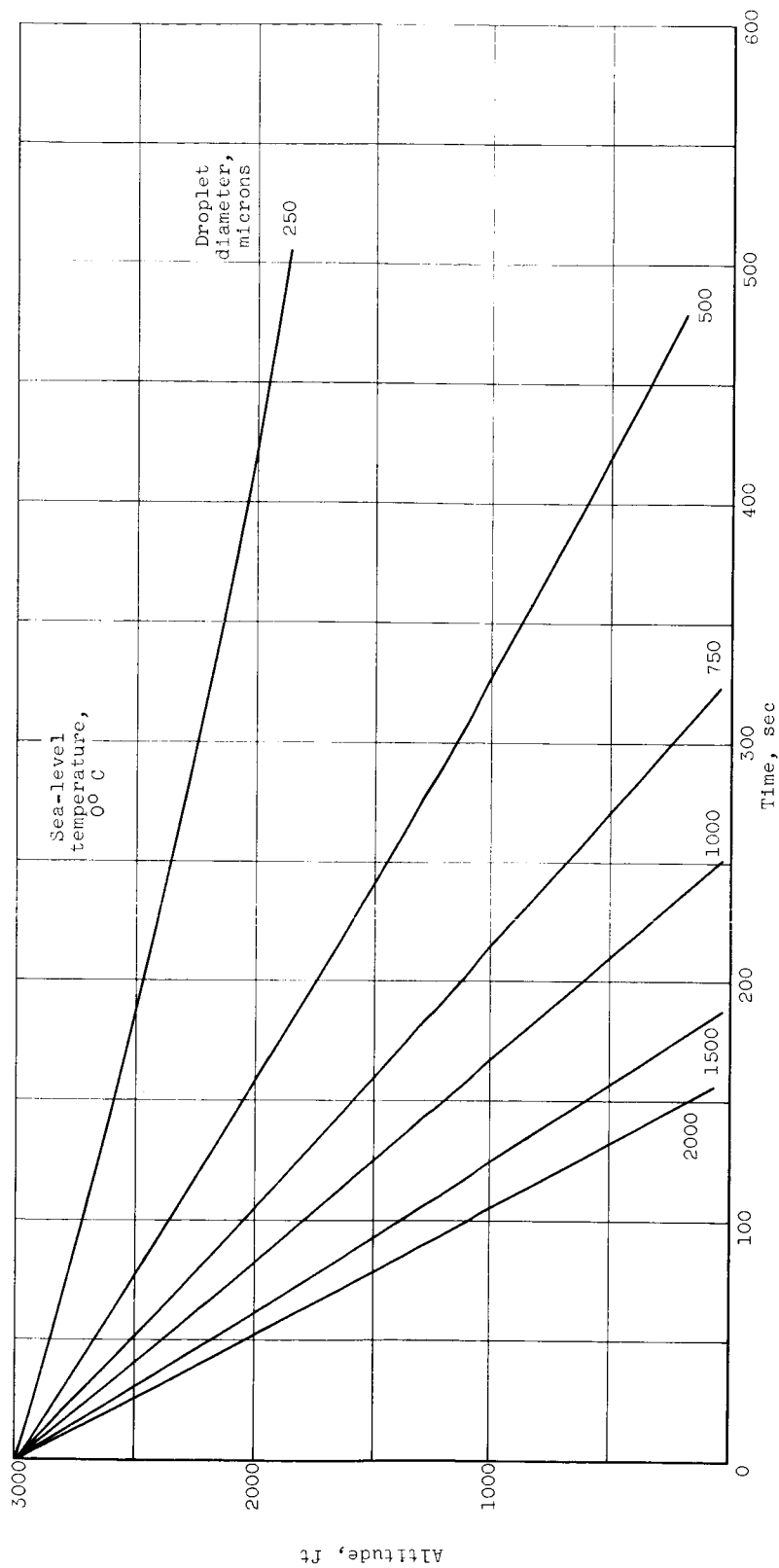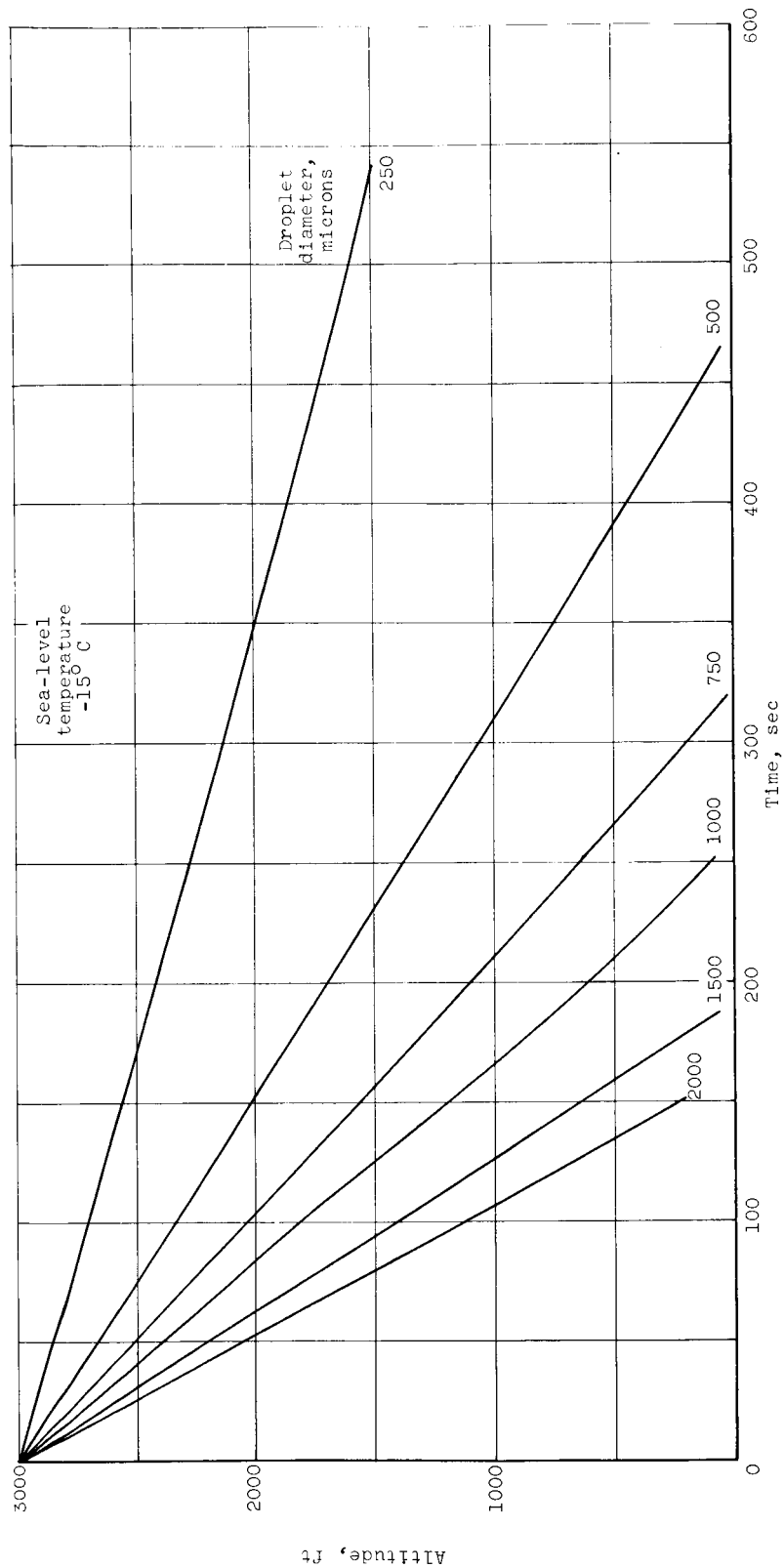(f) Continued. Starting altitude, 3000 feet.
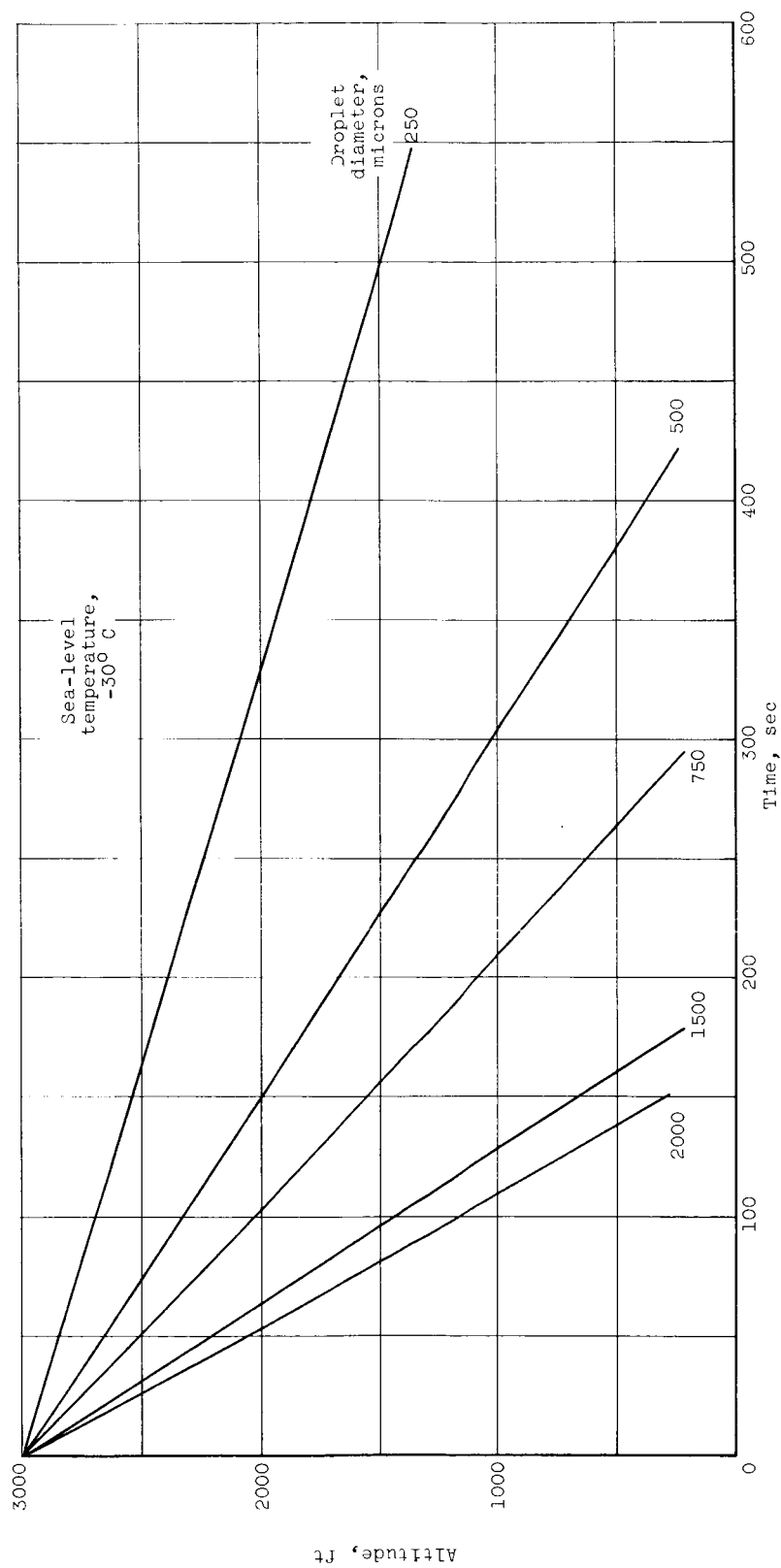
Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures.
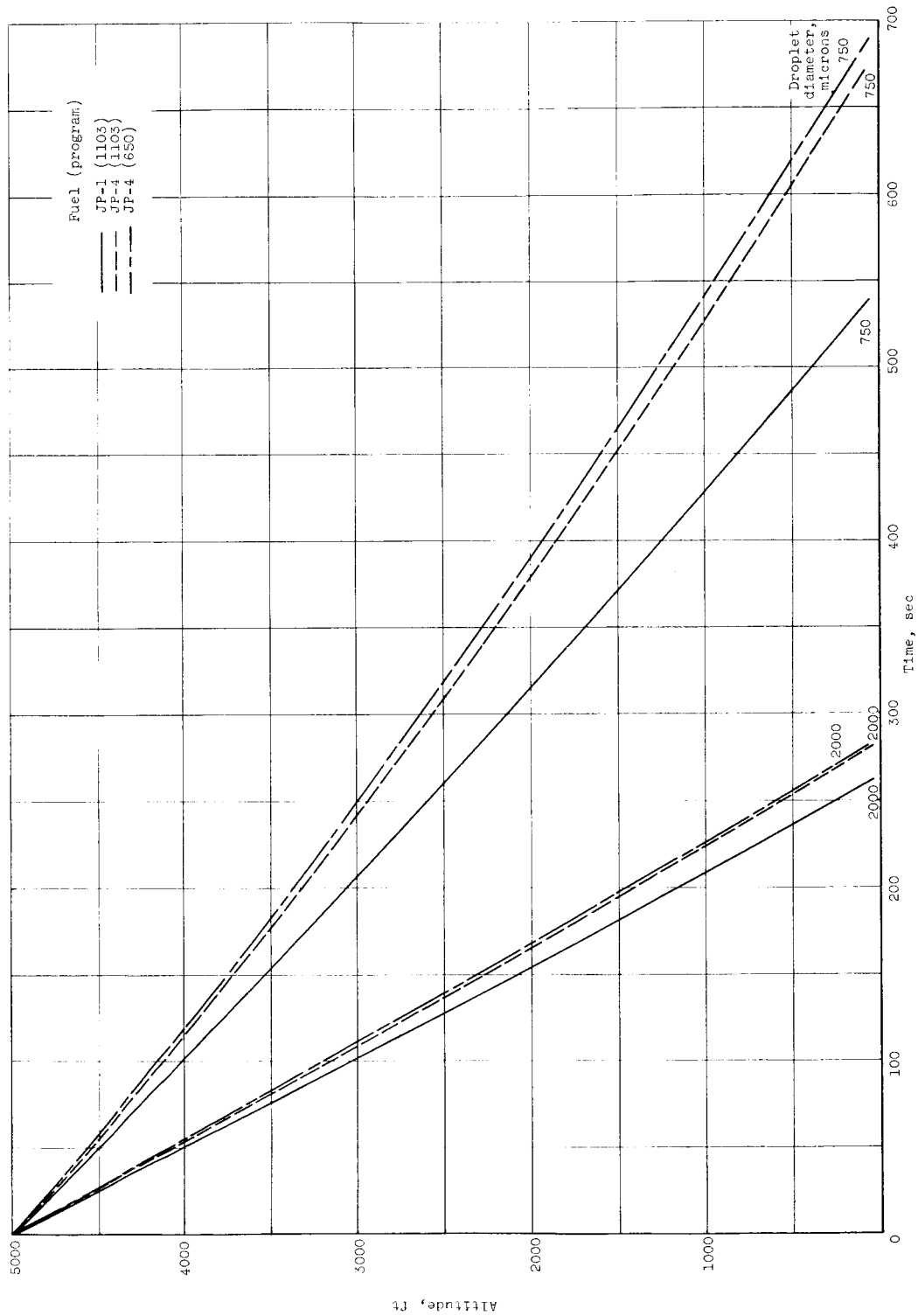Fuel, JP-1.

(f) Continued. Starting altitude, 3000 feet.

Figure 1. - Continued. Droplet altitude as function of time after release at fixed sea-level air temperatures.
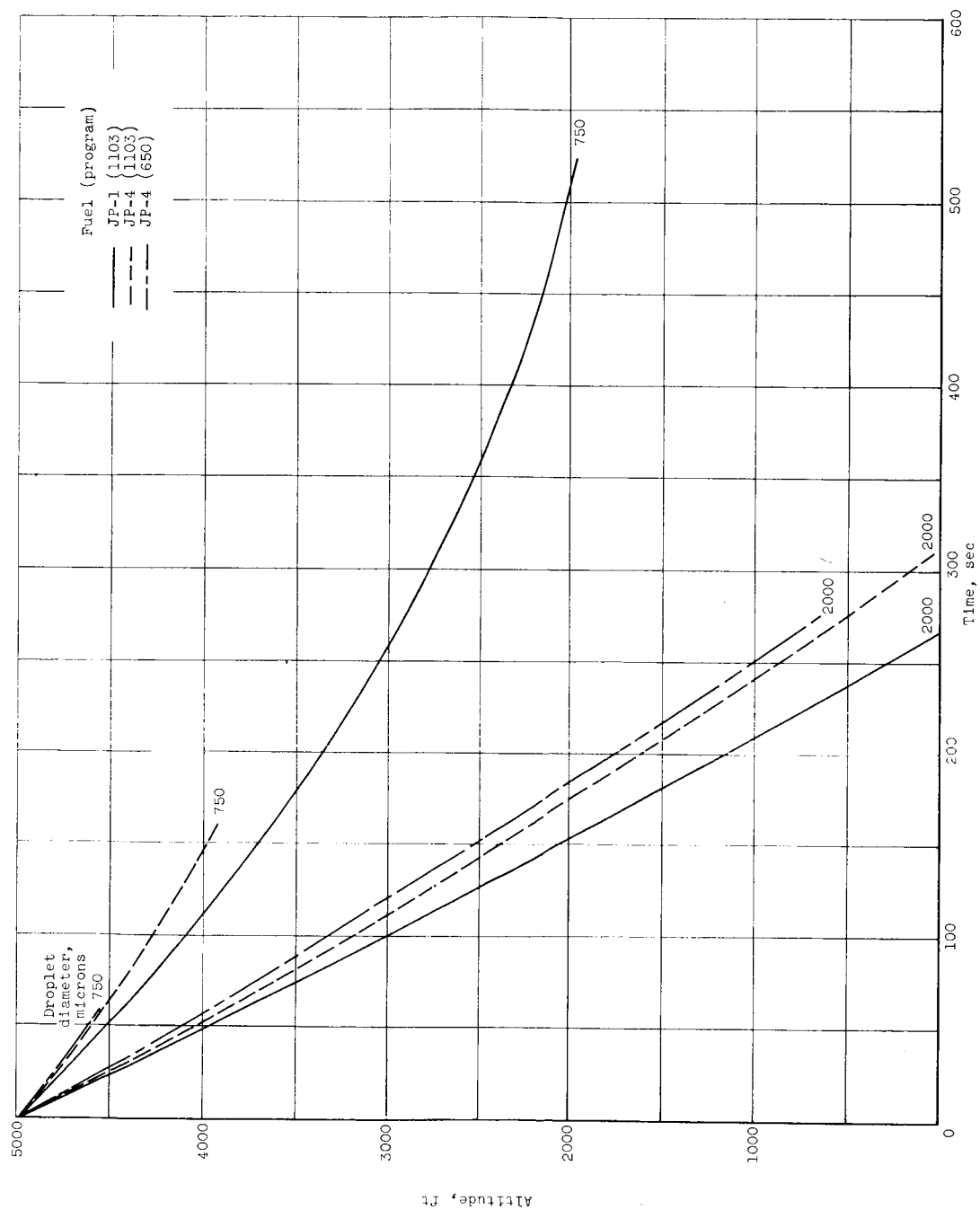Fuel, JP-1.

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(f) Concluded. Starting altitude, 3000 feet.

Figure 1. - Concluded. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuel, JP-1.

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(a) Sea-level air temperature, 0° C.

Figure 2. - Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuels, JP-1 and JP-4; starting altitude, 5000 feet.

Figure 2. - Concluded. Droplet altitude as function of time after release at fixed sea-level air temperatures. Fuels, JP-1 and JP-4; starting altitude, 5000 feet.
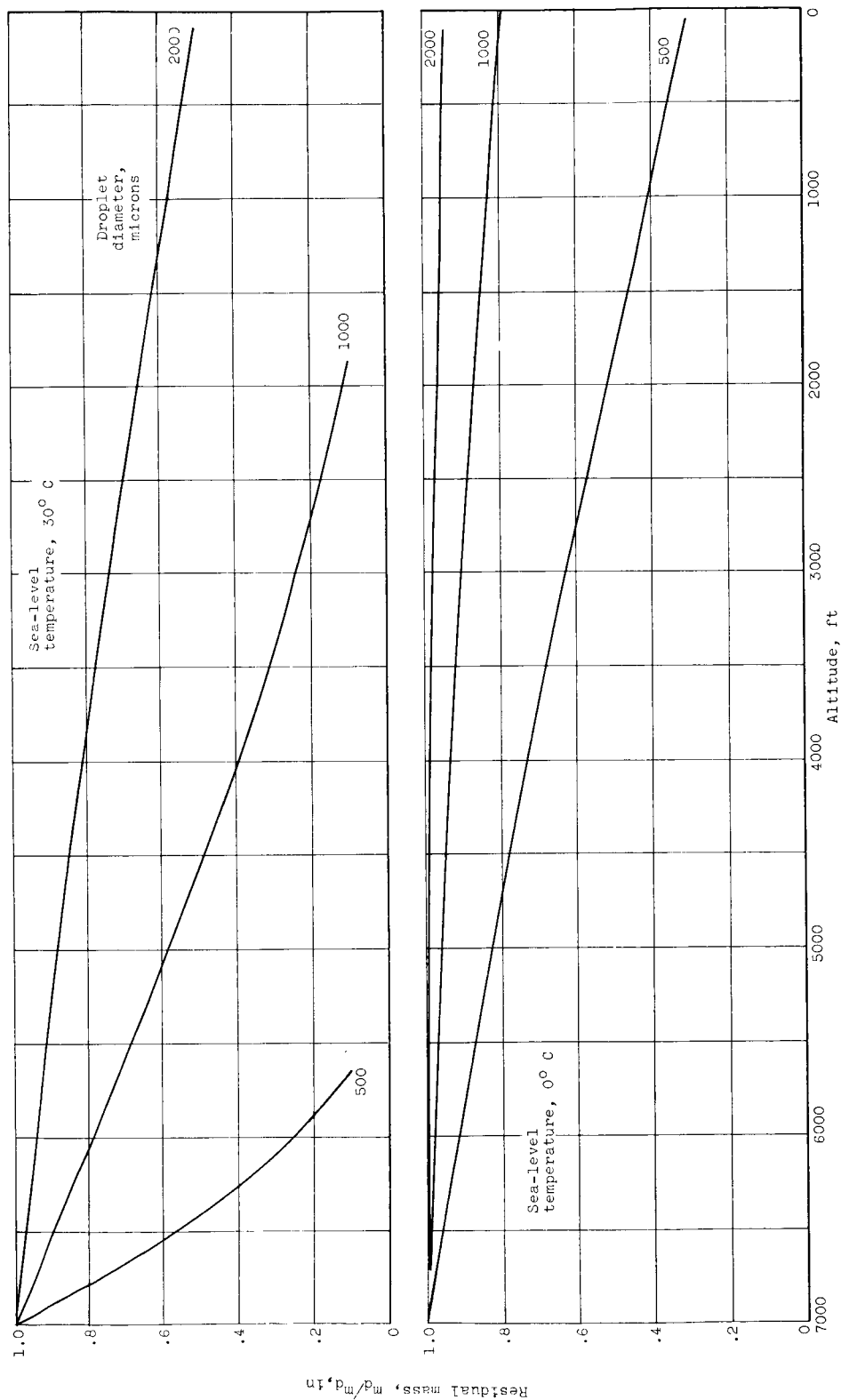
(b) Sea-level air temperature, 30° C.

(a) Starting altitude, 7000 feet.

Figure 3. - Residual mass as function of altitude at fixed sea-level air temperatures. Fuel, JP-1.

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(b) Starting altitude, 5000 feet.

(c) Starting altitude, 3000 feet.

Figure 3. — Continued. Residual mass as function of altitude at fixed sea-level air temperatures. Fuel, JP-1.
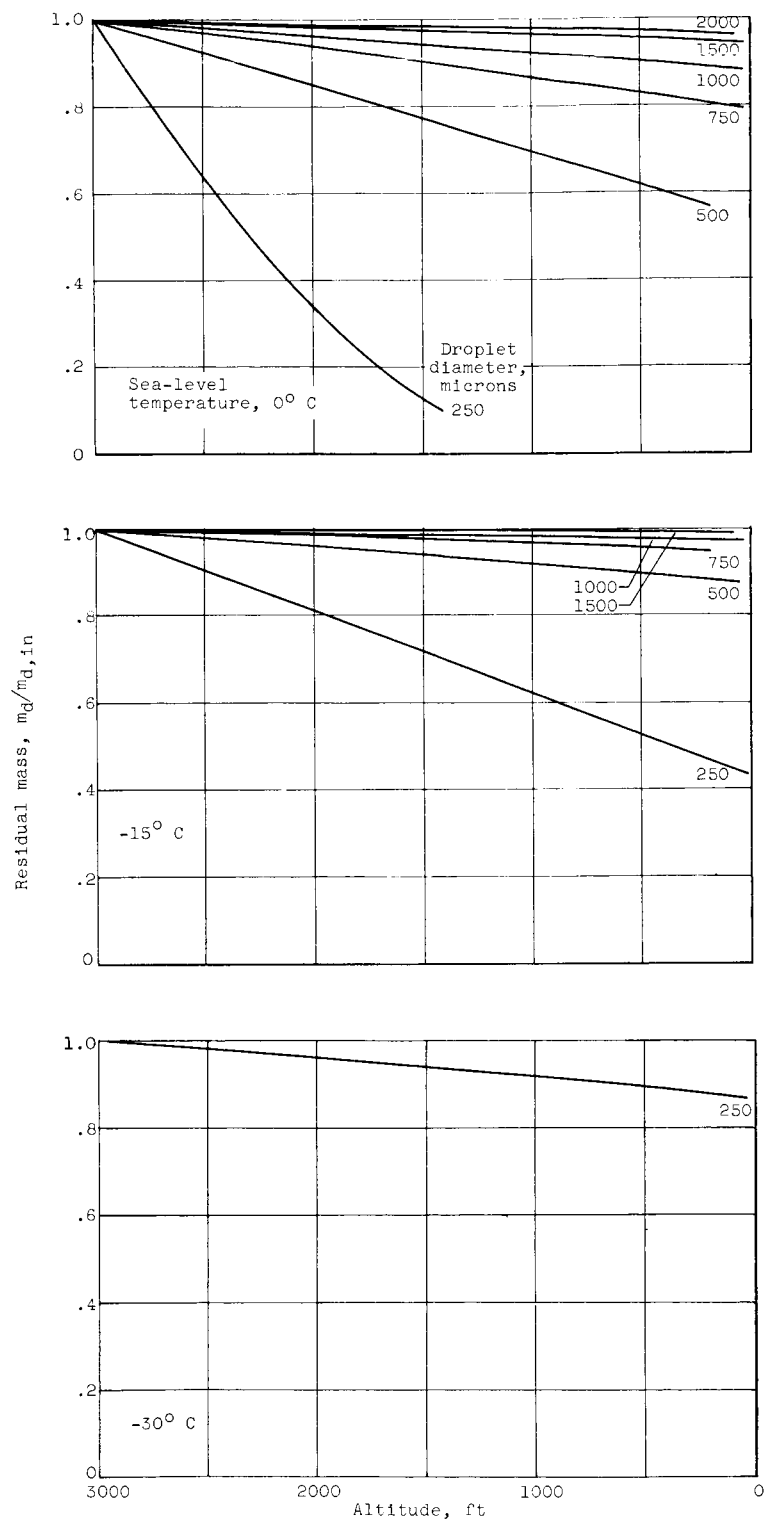
(c) Concluded. Starting altitude, 3000 feet.

Figure 3. - Concluded. Residual mass as function of altitude
at fixed sea-level air temperatures. Fuel, JP-1.

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, CN-6, back

2000

750

2000

Droplet
diameter,
microns

750

Fuel (program)

JP-1 (1103)
JP-4 (1103)

(a) Sea-level air temperature, 0° C.

2000

2000

750

750

Altitude, ft

(b) Sea-level air temperature, 30° C.

Residual mass, $m_d/m_{d,in}$

1.0

.8

.6

.4

.2

0

5000

4000

3000

2000

1000

0
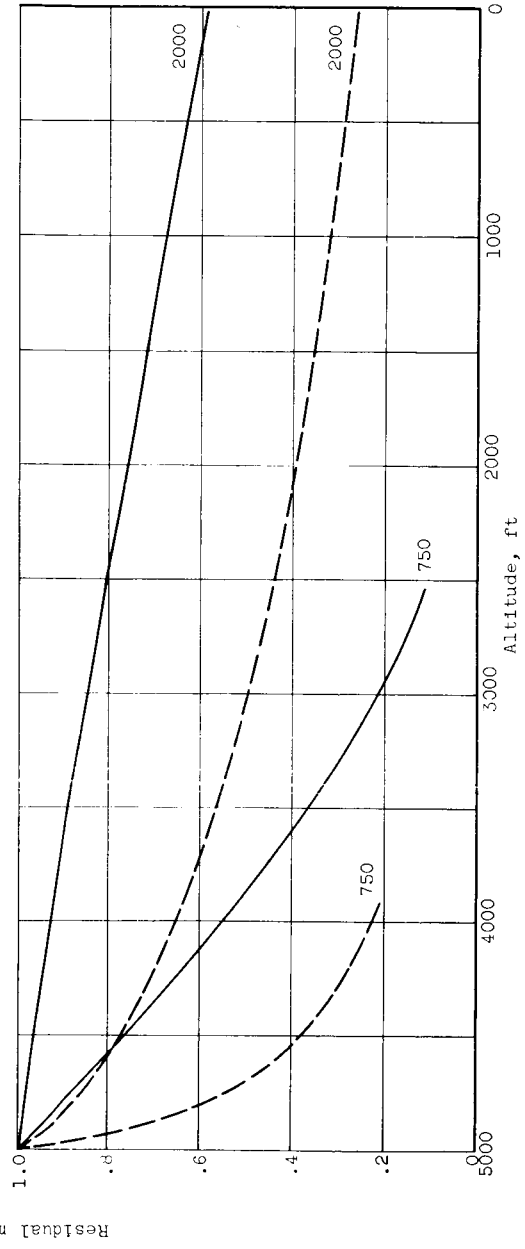
Figure 4. - Residual mass as function of altitude at fixed sea-level air temperatures. Fuels, JP-1 and JP-4; starting altitude, 5000 feet.

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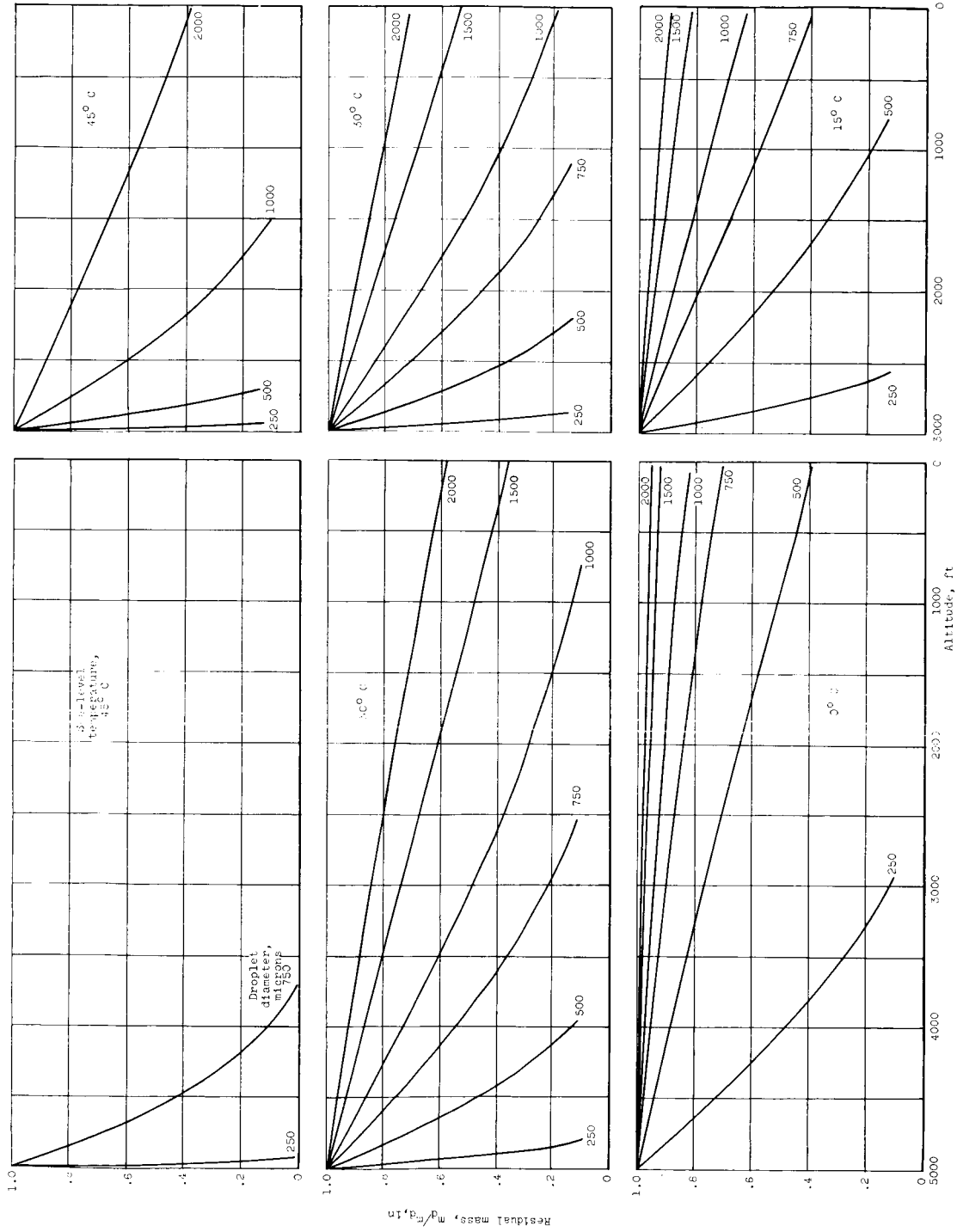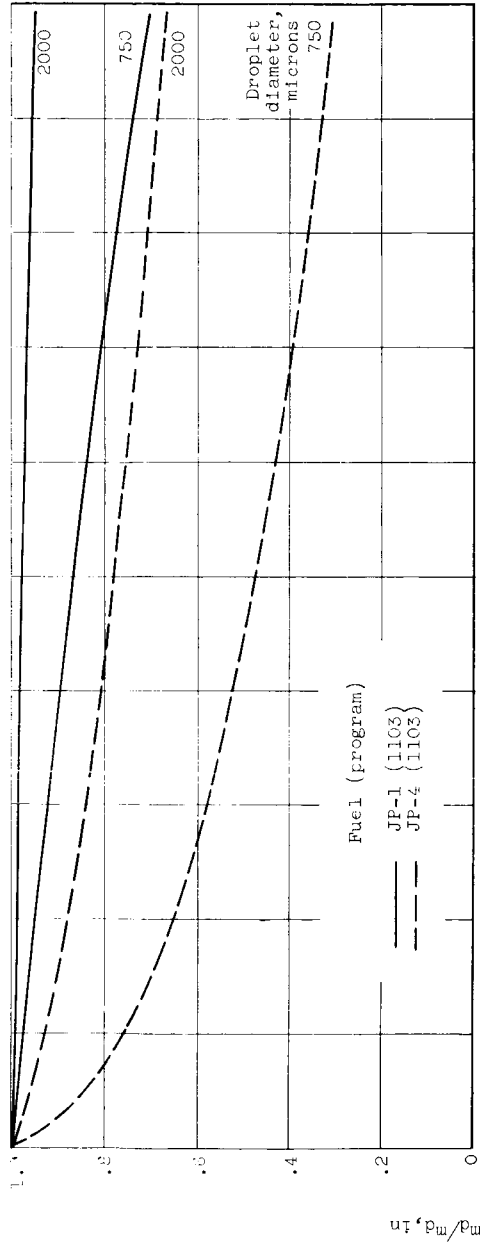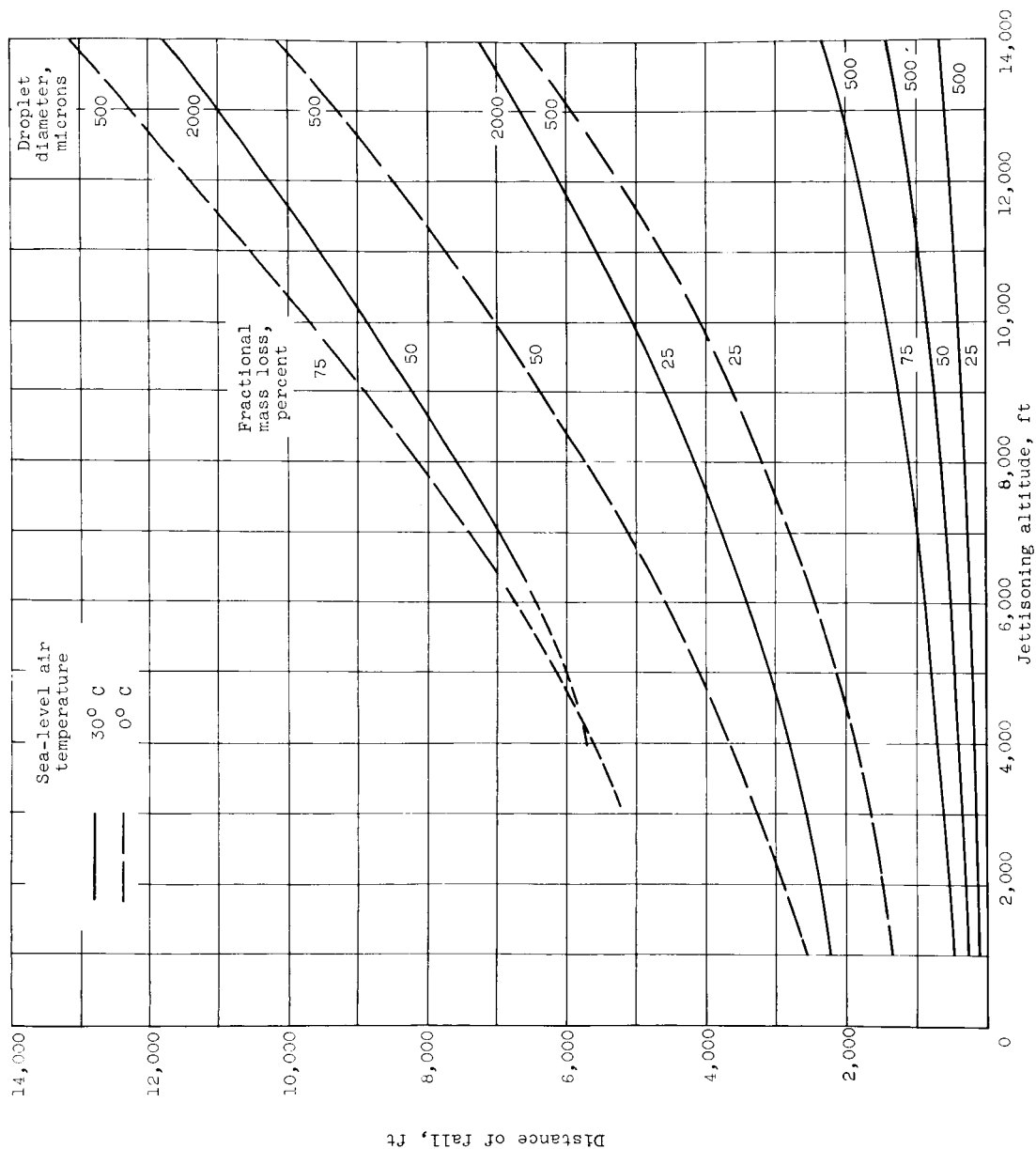Figure 5. - Variation with jettisoning altitude of distances of fall for fixed total fractional mass losses. Fuel, JP-1.
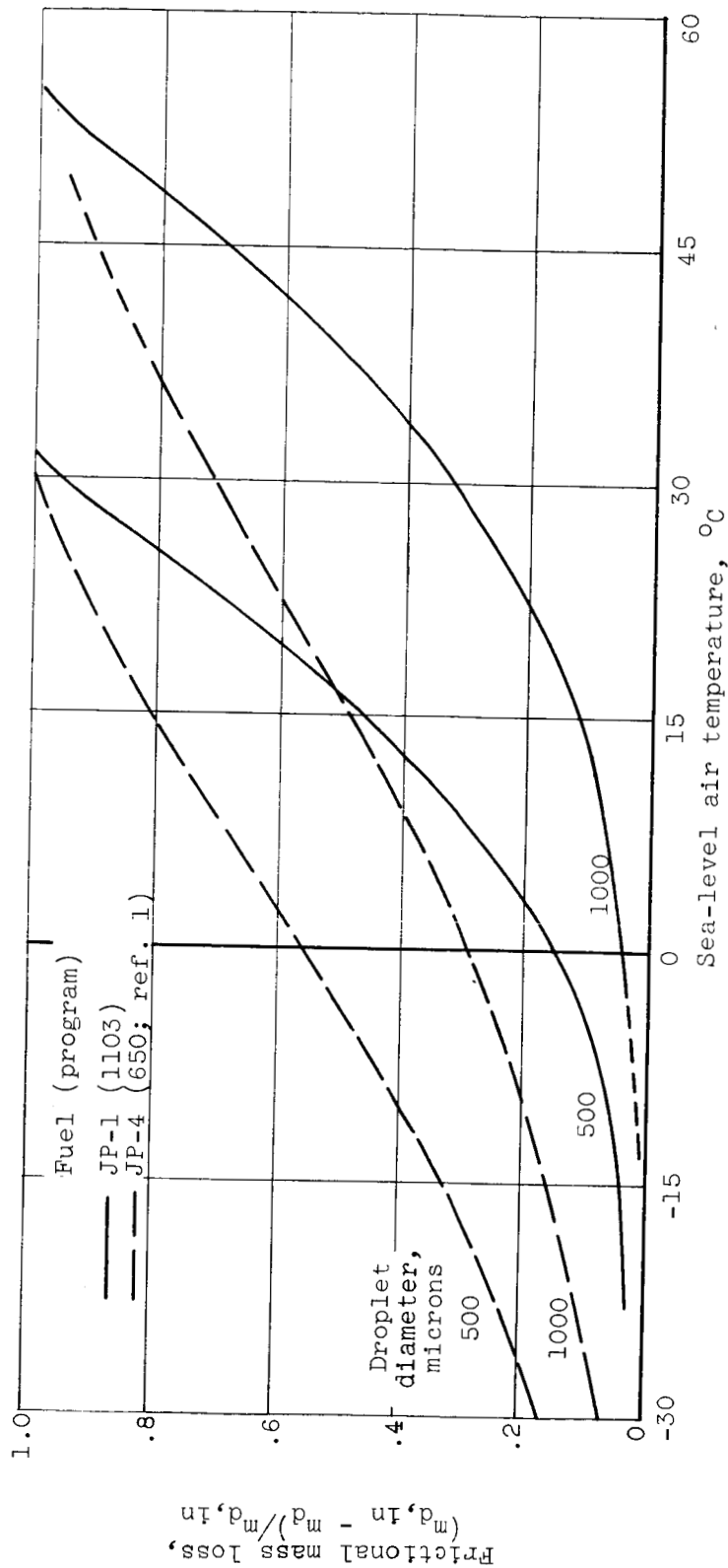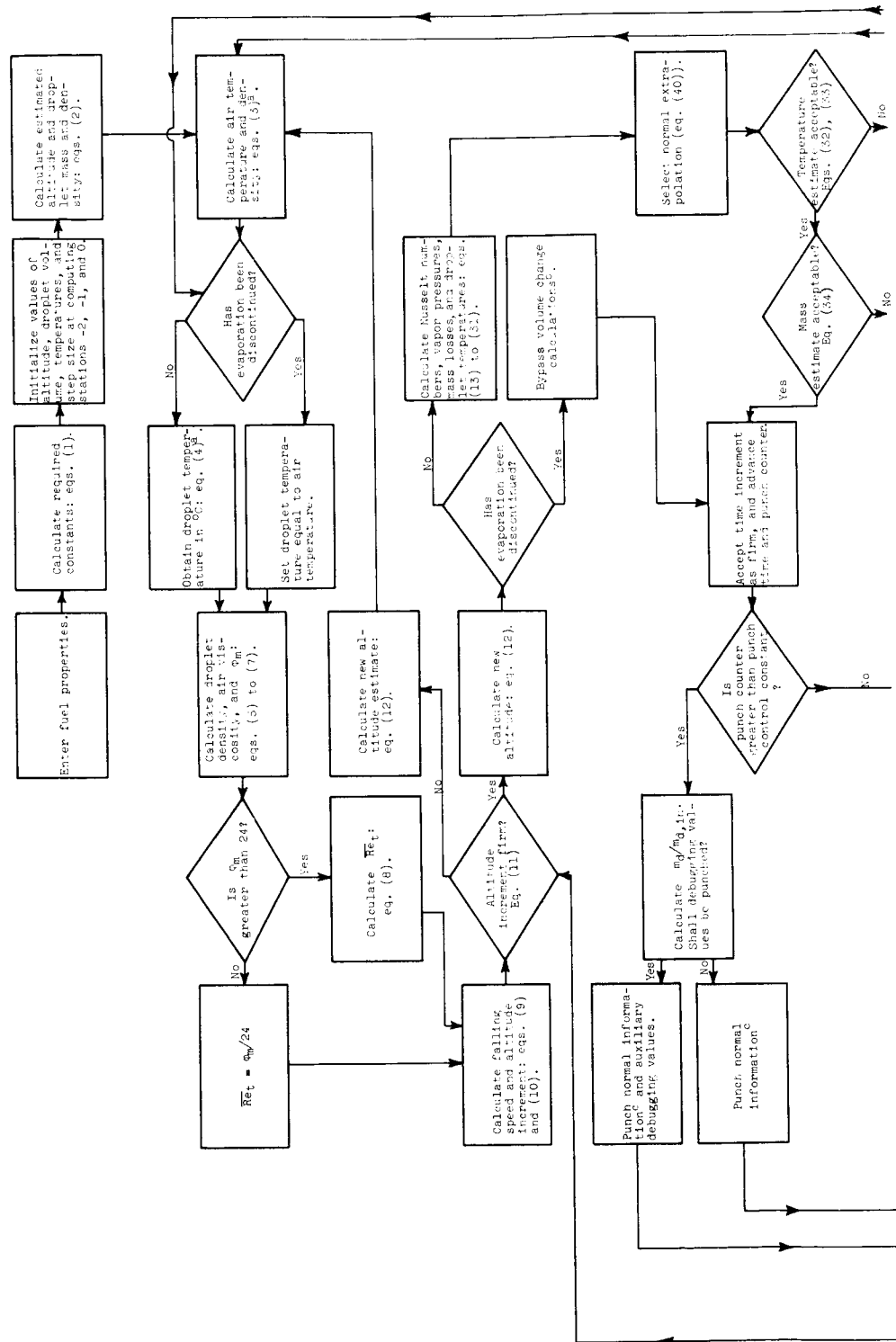
Figure 6. - Fractional mass lost by droplet during fall of 1000 feet as function of air temperature. Starting altitude, 3000 feet.

Enter fuel properties.

Calculate required constants: eqs. (1).

Initialize values of altitude, droplet vol- ume, temperatures, and step size at computing stations -2, -1, and 0.

Calculate estimated altitude and drop- let mass and den- sity: eqs. (2).

Calculate air tem- perature and den- sity: eqs. (3).

Has evaporation been discontinued?

Obtain droplet tempera- ture in °C: eq. (4).

Set droplet tempera- ture equal to air temperature.

Calculate droplet density, air vis- cosity, and ϕ_m: eqs. (5) to (7).

Is ϕ_m greater than 24?

Calculate $\overline{Re}$: eq. (8).

$\overline{Re} = \phi_m/24$

Calculate falling speed and altitude increment: eqs. (9) and (10).

Altitude increment firm? Eq. (11).

Calculate new alti- tude estimate: eq. (12).

Calculate new altitude: eq. (12).

Calculate Nusselt num- bers, vapor pressures, mass losses, and drop- let temperatures: eqs. (13) to (32).

Has evaporation been discontinued?

Bypass volume change calculations.

Select normal extra- polation (eq. (40)).

Temperature estimate acceptable? Eqs. (32), (33)

Mass estimate acceptable? Eq. (34)

Accept time increment as firm, and advance time and punch counter.

Is punch counter greater than punch control constant?

Calculate $m_d/m_{d,1r}$; Shall debugging val- ues be punched?

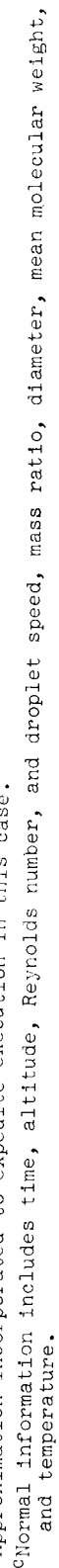Punch normal informa- tion and auxiliary debugging values.

Punch normal information

No   Yes

Figure 7. – ERA 1103 computer program diagram.

aInitialized value used prior to first completion of loop.

bApproximation incorporated to expedite execution in this case.

cNormal information includes time, altitude, Reynolds number, and droplet speed, mass ratio, diameter, mean molecular weight, and temperature.

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